The Dissertation Committee for Amanda Dulcinea Cuéllar Certifies that this is the approved version of the following dissertation:

Climate Change Adaptation to Increasing Risk of Glacial Lake Outburst Floods: Decision Making Methodology for Risk Management Applied to Imja Lake in Nepal and Lake Palcacocha in Peru

Committee:

Daene C. McKinney, Supervisor

Dale O. Stahl, II

Paola Passalacqua

Michael E. Webber

Robert Gilbert

Climate Change Adaptation to Increasing Risk of Glacial Lake Outburst Floods: Decision Making Methodology for Risk Management Applied to Imja Lake in Nepal and Lake Palcacocha in Peru

by

Amanda Dulcinea Cuéllar, B.A.; B.S. Ch.E.; M.S.

Dissertation

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

The University of Texas at Austin

August, 2016

Dedication

I would like to dedicate this work to my family. To my husband, Joe, and son, Julian, my tireless supporters; to my parents, Yolanda and Jesús, who taught me that such an achievement is possible; to my grandfather, Jesús, who taught me the value of an education and hard work; and to my sisters, Julieta and Victoria, my best friends through it all.

Acknowledgements

I would like to acknowledge the kind contribution of members of the McKinney research group to this work including Denny Rivas, Dave Rounce, Rachel Chisholm and Marcelo Somos-Valenzuela. I also had the privilege of working with Antonio Cañamás Catalá, who contributed to the vulnerability portion of this work. I would like to thank the US Army Corps of Engineers and William Lehman for their help with the HEC-RAS program and allowing me to beta test the model. Thanks to Dr. Jesús Cuéllar Fuentes for advice and guidance on methods for statistical analysis in the vulnerability portion of this work. I appreciate the advice of César Portocarrero for the Peru site. I would like to thank the dissertation committee for reviewing and offering recommendations for this work. Finally I would like to acknowledge and thank Daene McKinney for guiding me through the PhD process and writing of this dissertation.

I would like to acknowledge the financial support of the National Science Foundation Graduate Research Fellowship, the Bruce B. Jackson Endowed Graduate Fellowship in Engineering, and the National Science Foundation Dynamics of Coupled Natural and Human Systems program.

Many thanks to my family for their support, encouragement, and patience.

Climate Change Adaptation to Increasing Risk of Glacial Lake Outburst Floods: Decision Making Methodology for Risk Management Applied to Imja Lake in Nepal and Lake Palcacocha in Peru

Amanda Dulcinea Cuéllar, PhD

The University of Texas at Austin, 2016

Supervisor: Daene C. McKinney

Glacial retreat around the world, accelerated by climate change, has led to the formation of glacier lakes that present a risk of a glacial lake outburst flood (GLOF). GLOFs are sudden, catastrophic events that are impossible to predict. Communities in the path of a potential GLOF are now attempting to implement adaptation projects, yet no quantitative data or guidance is available to understand the benefits of adaptation projects or how to weigh these benefits against the cost of project implementation. The objective of this work is to develop a rational decision making methodology for GLOF risk management that incorporates available scientific information and the uncertainty surrounding the understanding of GLOF events. The decision making methodology consists of 1) identifying flooding scenarios, 2) evaluating the consequences of flooding scenarios, and 3) a nuanced (in terms of the inclusion of intangibles and probabilistic events) economic analysis of flood consequences and adaptation options. The methodology is applied to Lake Palcacocha in Peru and Imja Lake in Nepal to demonstrate the robustness of the methodology in light of different sources of uncertainty and data gaps. For Imja Lake it is concluded that lowering the lake 10 m is the best decision, from an economic standpoint. Nonetheless, the decision is sensitive to changes in the decision tree variables, which should be assessed for accuracy. At Lake Palcacocha it was determined that a GLOF would result in substantial damage to the city of Huaraz and the best decision is to lower the lake 30 m and install an emergency warning system (EWS). This decision is robust to large changes in the uncertain variables.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

BACKGROUND

High altitude glaciated regions of Peru and Nepal have experienced glacial retreat since the end of the Little Ice Age (Carey et al. 2011; ICIMOD 2011). The effects of a changing climate have accelerated the process of glacial lake formation and growth (Carey et al. 2011; Eriksson et al. 2009; Rabatel et al. 2013). As glaciers retreat melt water often collects at the base of the ice behind a natural dam (termed moraine) of rocks, soil and debris pushed forward by the previously expanding glacier (Portocarrero 2014). Terminal moraines tend to be unstable (Eriksson et al. 2009), in part because they often contain ice that is also melting (Portocarrero 2014). When a terminal moraine fails because of pressure from the growing lake, an avalanche triggered wave or an earthquake, the sudden outflow of water can cause devastation to downstream communities (Kattelmann 2003; Portocarrero 2014). The threat of a glacial lake outburst flood (GLOF) results from the complex interactions of multiple physical phenomena. Stability of the slopes above the glacial lake and of the moraines (terminal and lateral), dynamics of the glacier and lake over time and fluid dynamics in the lake and of the flood downstream converge to produce a GLOF event (Carey et al. 2011; Portocarrero 2014; Somos-Valenzuela et al. 2016). GLOF risk mitigation strategies usually consist of draining water from the glacial lakes and lowering the lake level. By lowering the lake level, pressure on the moraine will decrease and the surge of water flowing downstream will be less in the event of a flood, resulting in a smaller inundation area (Portocarrero 2014; Somos-Valenzuela et al. 2015; Somos-Valenzuela et al. 2016).

The physical phenomena contributing to GLOF risk have been studied extensively in the literature (Awal & Nakagawa 2010; Bajracharya & Mool 2010; Carrivick 2010; Hock 2005; Petrakov et al. 2011; Rabatel et al. 2013; Reynolds Geo-Sciences 2003; Schneider et al. 2014; Vilímek et al. 2005; Watanabe et al. 2009) and by members of the authors' research group (Byers et al. 2013; Rounce & McKinney 2014; Somos-Valenzuela et al. 2015; Somos-Valenzuela et al. 2016; Rounce et al. 2016). To date the authors' research group has succeeded in modeling a GLOF and estimating its characteristics for Imja (Somos-Valenzuela et al. 2015) and Palcacocha lakes (Somos-Valenzuela et al. 2016). These studies use fluid dynamic and debris flow models to simulate a particular GLOF scenario and predict the area downstream that would be affected as well as physical characteristics of the flood such as velocity, depth, and time of arrival. Modeling at Imja Lake considers a flood with the lake at current levels and with several lake lowering measures to mitigate the damage of a GLOF (Somos-Valenzuela et al. 2015). For Lake Palcacocha Somos-Valenzuela et al. (2016) simulated the maximum possible flood from the lake under current conditions as well as floods that could occur with various lake lowering works. The wave generated by an avalanche into the lake and dynamics when a wave overtops the terminal moraine were modeled. These results were combined with a downstream inundation model to understand how the wave translates into a flood. All of these results consider particular scenarios in terms of the triggering event and its magnitude. Several assumptions regarding the GLOF trigger and progression must be made because of a lack of data about the most likely characteristics of the trigger mechanism and the constitution and stability of the moraine. Other approximations and simplifications are made in the models to facilitate the solution of complex momentum and continuity equations for fluid flow (for instance use of roughness factors, two dimensional modeling, etc.) (FLO-2D 2009).

Few researchers have focused on translating their results into quantitative vulnerability, risk, and economic assessments for use in the decision making process (Carey et al. 2011; Rana et al. 2000; Schneider et al. 2014). The task of developing quantitative information that conveys the risk of a potential GLOF is complicated by the difficulty of assigning a probability to a GLOF event or margin of error to modeling results. Modeling each of the physical processes involved in generating a GLOF introduces uncertainty from model and parameter approximations (Somos-Valenzuela et al. 2015). In addition, scientists studying GLOFs cannot know what mechanism will trigger a GLOF, the details of the triggering event, or timing of such an event. Previous studies address these shortcomings through scenario analysis to capture the range of likely damage from a GLOF (ICIMOD 2011; Rana et al. 2000; Schneider et al. 2014).

Although researchers have made significant advances in understanding and modeling GLOF scenarios, the information has not been analyzed with risk assessment or decision making in mind. In particular, only two studies have attempted to quantify the range of likely floods from both lakes considered here with and without adaptation works (Somos-Valenzuela et al. 2015; Somos-Valenzuela et al. 2016). In addition only one researcher has addressed the range of potential consequences of a GLOF in terms of loss of life and social damages (Somos-Valenzuela 2014) and no other works have estimated direct economic impacts from a GLOF with and without adaptation measures. Finally, researchers have not proposed a means for evaluating the costs and benefits of various adaptation options that takes into account the available data and reflects the extreme uncertainty surrounding GLOF prediction.

Objectives

The objective of this work is to develop a rational decision making methodology for GLOF risk management that incorporates available scientific information and the uncertainty surrounding the understanding of GLOF events. In particular the decision making methodology consists of: (1) identifying potential flooding scenarios, (2) evaluating the consequences of flooding scenarios, and (3) a nuanced (in terms of the inclusion of intangibles and probabilistic events) economic analysis of flood consequences and adaptation options. The outcome of this work is the application of the risk management methodology to Palcacocha Lake in Peru and Imja Lake in Nepal to demonstrate the robustness of the methodology in light of different sources of uncertainty and data gaps. The results of the work will help to inform decision makers concerned with the GLOF risk, especially from Palcacocha and Imja lakes, and provide a procedure for communities threatened by GLOFs to evaluate adaptation options. In addition this work provides a general framework for risk management under uncertainty and demonstrates the use of novel analytical tools in risk management situations with limited data and extreme uncertainty.

The work reported here consists of a methodology to fill the knowledge gaps identified above. This methodology draws from the disciplines of economics, operations research, social sciences, and statistics to make the most of existing data and realistically represent uncertainty. The methodology consists of four components: defining flood scenarios, modeling flood extent, estimating flood damage, and analyzing economics of plans to minimize the risk posed by glacial lakes. In particular expert opinions of how a GLOF may be triggered and unfold are used to identify scenarios that represent the possible flooding outcomes. Modeling results of the flooding downstream resulting from the identified scenarios are used to estimate the potential inundation extent from a GLOF. The consequences of a GLOF are estimated in the communities downstream using flood damage methodologies developed in the literature. Finally, the costs and benefits of the various GLOF and flood mitigation scenarios (adaptation projects) are weighed using methodologies that allow for the inclusion of probabilistic information and intangible (i.e., no market price) consequences of a flood.

This work is organized as follows: Chapter 2 contains a methods section which details the decision making methodology developed here; Chapter 3 presents the application of the decision making methodology to Imja Lake in Nepal; in Chapter 4 the decision making methodology is applied to Lake Palcacocha in Peru; Chapter 5 contains conclusions and future work.

Chapter 2: Methods of Analysis

INTRODUCTION

The risk management methodology presented in this work is composed of a series of analytical procedures meant to quantitatively include the existing knowledge regarding GLOF risks, reflect the uncertainty regarding the occurrence, timing, and characteristics of a flood, and incorporate stakeholder concerns. Scenario analysis is used to assess the range of possible flood characteristics of a GLOF from Imja and Palcacocha lakes with and without adaptation projects. Consequences of potential GLOF events are estimated using the results of the scenario analysis with established flood damage methodologies for loss of life and direct economic losses (Graham, 1999; Lehman & Needham, n.d.; USACE, n.d.; USDHS, 2011a). In addition the Social Vulnerability Index (SoVI) (Cutter, Boruff, & Shirley, 2003) is adjusted for GLOF hazards to understand the social effects of a flood when data permits. The GLOF risk mitigation alternatives are evaluated taking into account their effectiveness in decreasing flood damage and cost using Data Envelopement Analysis (DEA) (Kuosmanen & Kortelainen, 2007; Womer et al., 2006) and Decision Analysis (DA) (Keeney, 1982). Whereas DEA allows for the valuation of intangibles such as fatalities and social vulnerability, DA incorporates uncertainty both of the event characteristics and occurrence in time. A summary of the risk management methodology is shown in Figure 2.1 with alternatives for the analysis of high data and low data cases.

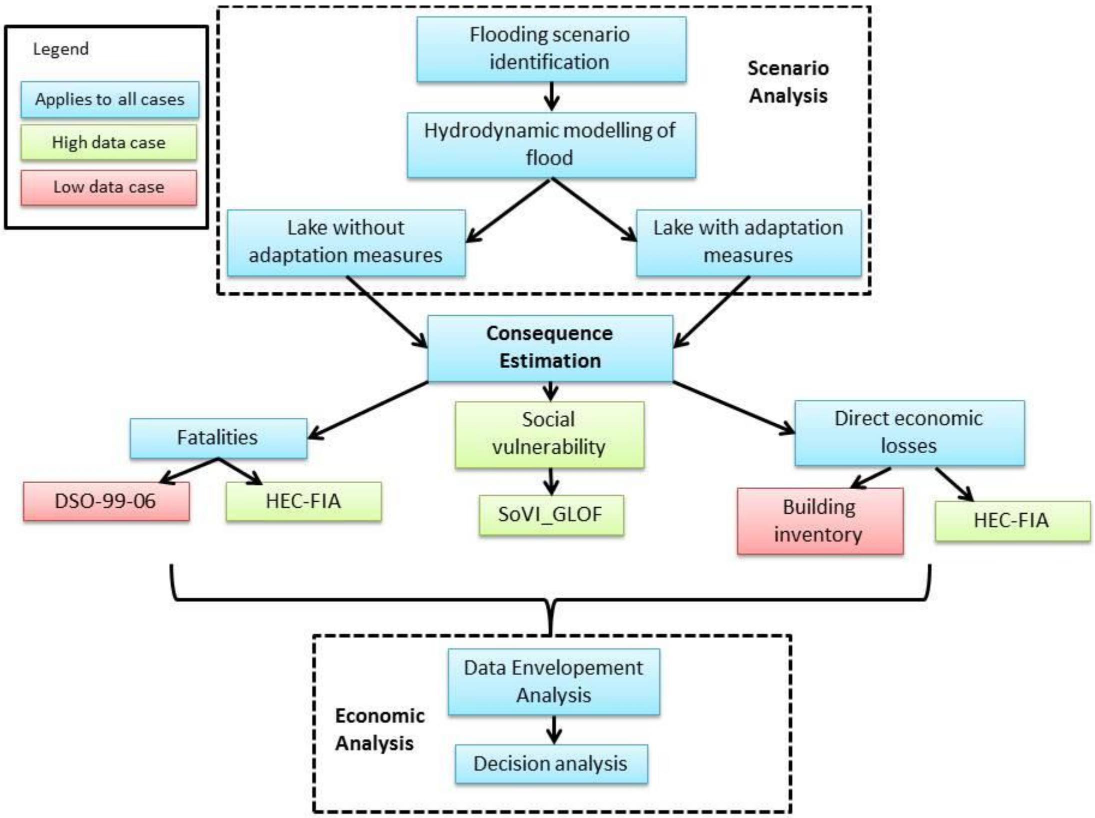

Figure 2.1. The GLOF risk management methodology includes alternatives for high data and low data cases.

Scenario Analysis

Given the uncertainty surrounding the occurrence and characteristics of a GLOF from Imja Lake and Lake Palcacocha, scenario analysis is used to consider likely flood events from each lake. The scenarios considered are a combination of potential GLOF triggering events or lack thereof combined with the effect of various GLOF mitigation works. This scenario ensemble is assembled to represent all likely GLOF triggers at the two lakes and to determine which decision is robust to the full set of likely futures (Lempert 2003).

A GLOF begins with a triggering mechanism, such as an avalanche into the lake, which causes overtopping or damage to the terminal moraine. In the event of an avalanche, a wave is generated that then overtops the moraine; the moraine may withstand the flow of water or fail, contributing more water to the flood flowing downstream. In the event of an earthquake or sudden destabilization of the moraine, the moraine may fail, resulting in a rush of water into areas downstream.

At Imja Lake the most likely flood trigger is sudden moraine failure due to an earthquake or destabilization of the moraine due to piping or melting of buried ice (Somos-Valenzuela et al. 2015). The moraine breach and resulting flood has been modeled using FLO-2D and HEC-RAS (Somos-Valenzuela et al. 2015).

At Lake Palcacocha the research group has consulted with experts to determine that the most likely GLOF trigger is an avalanche into the lake due to the steep, snow covered slopes above the lake (Emmer & Vilimek 2013; Somos-Valenzuela et al. 2016). The author's research group has also established a small, medium, and large avalanche scenario in consultation with experts. To date, members of the research group have simulated the dynamics of an avalanche into the lake, interaction of a wave with the terminal moraine, and the resulting flood into communities downstream. This work concluded that failure of the terminal moraine due to wave overtopping is not a likely outcome of the avalanche scenarios studied (Somos-Valenzuela et al. 2016).

The potential triggering events and their consequences considered in this work are summarized in Figure 2.2. Note that the avalanche scenario applies to Lake Palcacocha whereas the earthquake scenario applies to Imja Lake. Additionally, there is no evidence to suggest that a sudden moraine failure at Palcacocha Lake is a potential GLOF trigger.

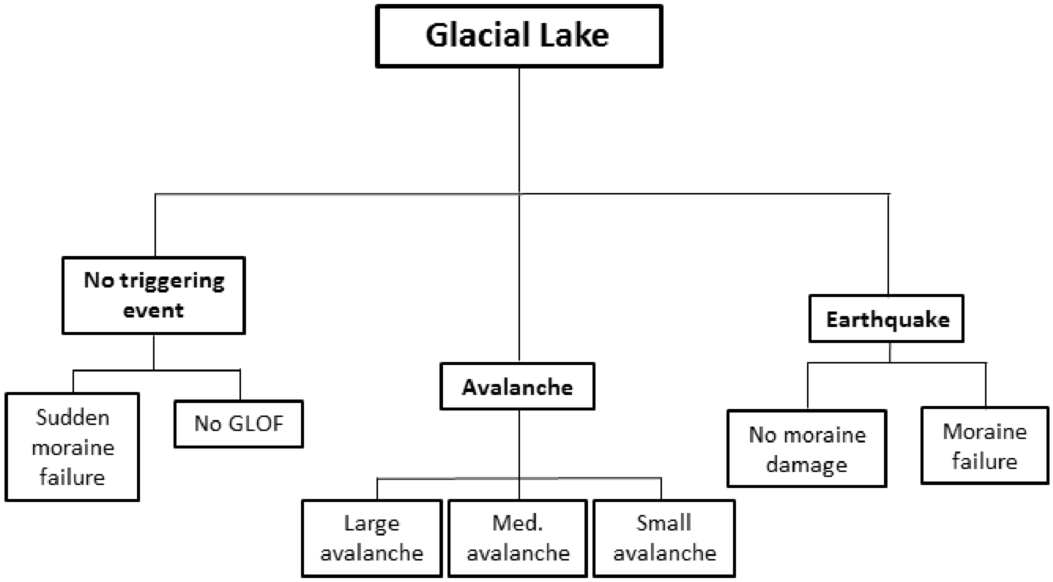

Figure 2.2. Potential triggering events and flooding scenarios from the glacial lake scenario analysis. The scenario analysis can be repeated for different states of the glacial lake (current conditions, future conditions, or after lowering)

The FLO-2D software models the physical processes of water as it flows overland or in a channel. FLO-2D uses a one dimensional wave approximation to the momentum equation in eight directions for each grid cell, which allows for multi directional flow estimation and manageable run times for complex flow geometries. (FLO-2D 2009) The research group chose to use FLO-2D because the software has sufficient complexity to model flow dynamics in the river channel and through a city such as Huaraz.

Scenario analysis results inform the development of GLOF hazard maps downstream of Imja and Palcacocha Lakes. In the past similar hazard maps have been used to inform community members and local governments of the potential effect of a GLOF in their region (Carey et al. 2011; Schneider et al. 2014). This work extends this methodology to consider how the consequences of GLOF scenarios will change with and without the implementation of proposed adaptation projects. The hazard maps generated here demonstrate how various adaptation plans will likely change the characteristics of a future GLOF and what benefits local communities may see.

CONSEQUENCE ESTIMATION

While scenario analysis estimates the physical characteristics of a potential flood, these results do not fully characterize the consequences of a GLOF. A flood will have public health and safety, economic (direct and indirect), psychological, and governance consequences (USDHS 2011a). Nonetheless, quantifying some of these categories in an absolute sense may be controversial or difficult to verify. Therefore in this work the quantitative assessment of consequences is focused on fatalities, direct economic losses from a GLOF, and an adapted social vulnerability index (a measure of the relative vulnerability of inhabitants to the social consequences of a flood).

Fatalities

Loss of life from a flooding event can be estimated through comparisons to historical events (empirical approach) or by modelling the dynamics of a population in the path of a flood and using depth-damage curves for people remaining in the flooded area (dynamic approach). Regardless of the method, fatalities depend on the number of people in the flood plain (population at risk), the amount of warning the population receives, and the severity of the flood event (Graham 1999; USDHS 2011b). One of the significant areas of improvement for flood fatality models is the definition of populations at risk (PAR). All existing models define PAR and subPAR (a subset of the PAR) by flood water velocity, water depth, flood type, population characteristics (including warning state) and, in some cases, location of the population (in a building or outside)

(Aboelata & Bowles 2005; McClelland & Bowles 2002). Some models include an assessment of population mobilization and evacuation from an at risk area in response to a warning. The model then applies a fatality rate to the population remaining in each subPAR that corresponds to the characteristics of the subPAR. Fatality rates are derived from depth-fatality curves which are in turn derived from historical floods; their appropriateness and validity depends in large part on the number of historical events included in their derivation and characteristics of these events. Models that simulate a population's evacuation (dynamic models) rely on experimental curves for the effect of water depth and velocity on pedestrian stability if individuals are caught in transit when the flood arrives. (McClelland & Bowles 2002) More advanced models are characterized by a finer subdivision of the PAR into subPAR, reliance on extensive and appropriate historical events for depth-damage curves, inclusion of detailed flood characteristic data, and simulation of a population's redistribution after issuance of a warning.

Several notable methodologies and models exist for estimating flood structure damage and fatalities. In selecting a methodology for the low and high data case assessed in this work, the most sophisticated model was chose given data constraints, models that were appropriate for a sudden, high velocity water flow, and models that could be applied to any location (not geographically specific). Models considered include: DSO-99-06, RCEM 2014, HEC-FIA, and Life Safety Model (LSM). Other models commonly used for flood damage estimation, such as HAZUS, were discounted because of their focus on non-dam break flooding events and geographic specificity (eg. HAZUS relies on US census data).

DSO-99-06

The DSO-99-06 methodology was developed for BUREC to provide a first estimate of dam failure fatalities using empirically derived fatality rates (Graham 1999; McClelland & Bowles 2002). For fatalities, the DSO-99-06 procedure (Graham 1999) relies on historical dam failure events in the United States to categorize the dam under consideration in terms of flood severity, warning time, and flood severity understanding; the method estimates fatalities using empirically derived fatality rates. Unlike other empirical methodologies, DSO-99-06 is the only approach that is appropriate for high lethality events with zero warning time (McClelland & Bowles 2002; Graham 1999). DSO-99-06 provides fatality estimates for three levels of flood severity, distinguished by the destructiveness of flood waters (are buildings unaffected, partially or completely washed from their foundations). The flood severity distinction makes this methodology well suited for a GLOF event. (Graham 1999) For the low data case (Imja Lake in Nepal) the DSO-99-06 methodology was used.

The methodology defines three flood severity levels, three warning time categories, and two levels of flood severity understanding. Flood severity understanding reflects how well officials in charge of issuing a warning understand the potential damage from an imminent flood, which in turn affects the urgency and effectiveness of a warning. Each combination of the three flood and warning characteristics is assigned a fatality rate derived from historical dam failure and similar flood cases. Unlike previous approaches, the DSO-99-06 uses an expanded data set including 40 floods from nearly all flood severity, warning time and flood severity understanding combinations. Table 2.1 contains the flood categories defined by DSO-99-06 and the fatality rate assigned to each category combination. (Graham 1999)

Table 2.1. Table of suggested fatality rates for different combinations of flood severity, warning time, and flood severity understanding as provided in Graham (1999).

<table>
<tr><th rowspan="2">Flood Severity</th><th rowspan="2">Warning Time (minutes)</th><th rowspan="2">Flood Severity Understanding</th><th colspan="2">Fatality Rate (Fraction of people at risk expected to die)</th></tr>
<tr><th>Suggested</th><th>Suggested range</th></tr>
<tr><td rowspan="5">High</td><td>No Warning</td><td>not applicable</td><td>0.75</td><td>0.3 to 1.00</td></tr>
<tr><td rowspan="2">15 to 60</td><td>vague</td><td colspan="2" rowspan="4">Use the values shown above and apply to the number of people who remain in the dam failure floodplain after warnings are issued. No guidance is provided on how many people will remain in the floodplain.</td></tr>
<tr><td>precise</td></tr>
<tr><td rowspan="2">more than 60</td><td>vague</td></tr>
<tr><td>precise</td></tr>
<tr><td rowspan="5">Medium</td><td>No warning</td><td>not applicable</td><td>0.15</td><td>0.03 to 0.35</td></tr>
<tr><td rowspan="2">15 to 60</td><td>vague</td><td>0.04</td><td>0.01 to 0.08</td></tr>
<tr><td>precise</td><td>0.02</td><td>0.005 to 0.04</td></tr>
<tr><td rowspan="2">more than 60</td><td>vague</td><td>0.03</td><td>0.005 to 0.06</td></tr>
<tr><td>precise</td><td>0.01</td><td>0.002 to 0.02</td></tr>
<tr><td rowspan="5">Low</td><td>no warning</td><td>not applicable</td><td>0.01</td><td>0.0 to 0.02</td></tr>
<tr><td rowspan="2">15 to 60</td><td>vague</td><td>0.007</td><td>0.0 to 0.015</td></tr>
<tr><td>precise</td><td>0.002</td><td>0.0 to 0.004</td></tr>
<tr><td rowspan="2">more than 60</td><td>vague</td><td>0.0003</td><td>0.0 to 0.0006</td></tr>
<tr><td>precise</td><td>0.002</td><td>0.0 to 0.0004</td></tr>
</table>

Graham provides both a description of the difference in physical destruction from a high, medium and low severity flood and a quantitative measure to distinguish each category. The quantitative measure is defined by the DV parameter defined in Equation 2.1.

$$DV = \frac{Q_{df} - Q_{2.33}}{W_{df}} \tag{2.1}$$

In Equation 2.1 $Q_{2.33}$ is the mean annual discharge at a given location, Q_{df} is the discharge after dam failure, and W_{df} is the maximum flooding width caused by the dam failure; all variables are for the same site. The DV parameter is an indicator of the level of destruction possible by flood water and is given in units of d^2/s (depth times velocity, although it is not a measure of these variables). Low severity events will have a DV less than 50 ft^2/s (4.6 m^2/s) and medium severity events will have a DV greater than 50 ft^2/s. No quantitative guidance is provided for high severity floods. Graham does, however, explain that a low severity event will not wash buildings off their foundations, a medium event will leave behind mangled homes or trees, and a high severity event will result in complete removal of buildings in the path of the flood. High severity events result in deep floods that reach their maximum depth quickly (in a matter of minutes). (Graham 1999)

DSO-99-06 requires little data to estimate fatalities. The user must know the maximum inundated area and judge whether the flood will be of high, medium or low severity. In addition the user must know the population residing in the flood area and estimate how this population will change if a warning is issued. With this information the user can identify the suggested fatality rate and range appropriate for the flood under consideration.

Regarding model validity, Graham recommends that researchers continue to expand the database of historical events and other methods to quantify fatality rates from high severity events, the least represented in the existing data set. In addition, Graham notes that fatalities depend on a variety of uncertain factors such as the time of day, time of week and time of year a dam failure occurs. The cause of a dam failure may also alter fatalities (sudden failure vs. a failure due to heavy rains and overtopping) as will user's judgment in determining the warning time for a dam failure. Graham suggests that users rely on a range of scenarios to explore the effect of various sources of uncertainty on fatalities from a flood event.

In general, empirical methodologies based on regression of historical events are most accurate when applied to scenarios similar to those in the method dataset (McClelland & Bowles 2002). Given the inclusion of various flood severity levels and low warning time floods (characteristic of a flood with no warning system, as is the case in Nepal) in the DSO-99-06 methodology, this approach is well suited for estimating loss of life from a GLOF at Imja Lake.

RCEM 2014

In 2014 the Bureau of Reclamations published an interim update to the DSO-99-06 methodology. The methodology is considered 'interim' pending further updates and clarifications once more experience is gained with the method. Updates made to the DSO method include new historical cases added to the dataset, reliance on a flood fatality graph instead of discrete ranges, reliance on quantitative DV values rather than flood severity, and elimination of flood severity understanding. Although the new method is very similar to the original DSO approach, it seeks to widen the range of dam failure situations covered, provide more quantitative guidance, and more closely reflect the information provided by historical cases. Authors of the new method also provide extensive instructions for the user to adapt the fatality rate and ranges to better reflect the particulars of the dam under study. (USBUREC 2014b)

A comparison of fatality estimations from the DSO methodology and RCEM shows that both methods provide similar fatality estimates. The RCEM method estimates, however, were usually lower than DSO estimates for instances where adequate warning is provided and higher than DSO in the case of rapidly developing dam failures. (USBUREC 2014b)

Despite the improvements in the new methodology, RCEM relies on DV values derived from flooding events that occurred mostly in western countries (in the category of high severity floods, only one event studied for RCEM occurred in South America; the rest occurred in the US, Japan, or Europe) (USBUREC 2014a). Therefore the depth and velocity characteristics of a high severity flood in the RCEM method may not be well suited to areas with different construction types. Given the use of DV values to assign flood severity, the method does not provide much flexibility in the definition of high, medium, and low severity. Therefore this work relies on the DSO-99-06 method, which, has been shown to have good agreement with the updated RCEM method.

HEC-FIA

USACE provides the HEC-FIA (Hydrologic Engineering Center's Flood Impact Analysis) (USACE 2016) for use in estimating the direct life loss and economic impacts of a flood event. In estimating loss of life, HEC-FIA makes use of the time of arrival, evacuation routes, and warning time for the flood to estimate how the population may relocate after a flood warning and more accurately estimate flood damage (USDHS 2011b; USACE 2016). USACE crafted the HEC-FIA life loss module to be quick to implement, accurate, and function with readily available demographic data to allow for low cost (time, data collection, and economic) dam failure consequence estimation (Lehman & Needham n.d.). To estimate fatalities and building damage HEC-FIA requires a digital elevation grid, structure inventory with population, inundation data, time of warning issuance, warning system information, mobilization information, information to estimate evacuation time, and parameters to define lethality zones and their fatality rates.

The life loss module of HEC-FIA is a simplified version of the LIFESim model developed by Aboelata and Bowles at Utah State University. In developing LIFESim, Aboelata and Bowles combined dynamic modelling of inhabitants with empirically derived damage and warning and mobilization curves. Although the simplified LIFESim retains many of the features of the full model, a notable omission is traffic modelling. In addition, earlier versions of the simplified LIFESim did not include the effect of water velocity on building stability and consequently fatalities of people trapped in buildings; this omission is rectified in the most recent version of the model. (USDHS 2011b; Aboelata & Bowles 2005) At present the simplified LIFESim model is managed and developed by the Army Corps of Engineers as a module of HEC-FIA. The model version described here is HEC-FIA 3.0.

The simplified LIFESim model (referred to as HEC-FIA from here on) simulates the reaction of a population to a flood warning, evacuation dynamics, and the effect of flood waters on those remaining in the flood plain. A flood simulation begins when an evacuation order (warning) is issued by the emergency management agency. The user defines both the time of initial warning for each geographic region in the model (user delineated) as well as the warning mechanism. HEC-FIA includes in-built warning diffusion curves for several warning systems. The warning diffusion curve specifies the percent of the targeted population that receives the warning as a function of time from initial issuance. Warning diffusion depends on warning system, warning type, and the activities people are engaged in when a warning is issued. The Rogers and Sorensen curve accounts for average daily time budget (time asleep, in transit, working, etc.) and the related effectiveness of various warning systems (for example, when a person is asleep they will not hear warnings broadcast on the radio) (Aboelata & Bowles 2005; Rogers & Sorensen 1991) and is used in HEC-FIA (Lehman & Needham n.d.). As people are warned, a mobilization curve is applied, which provides an estimate for the time from warning receipt to mobilization of the warned person (Lehman & Needham n.d.). Once residents are mobilized they continue evacuating until the no-evacuation condition is met at each grid cell (user defined water depth that halts evacuation; default is 2ft). Residents that do not mobilize with enough time to reach a safe zone are assigned to a lethality zone.

HEC-FIA relies on either a user defined evacuation time or a hazard polygon combined with nominal speed of evacuation. In the latter case, the model estimates evacuation time for each building using straight line distance to the hazard polygon (limit of flood danger) and nominal speed of evacuation. Because HEC-FIA does not measure distance along roads or include the effects of traffic congestion, the user must implicitly account for these constraints when choosing a nominal speed of evacuation. (Lehman & Needham n.d.) Figure 2.3 contains a graphic showing how evacuation outcomes are assigned in HEC-FIA.

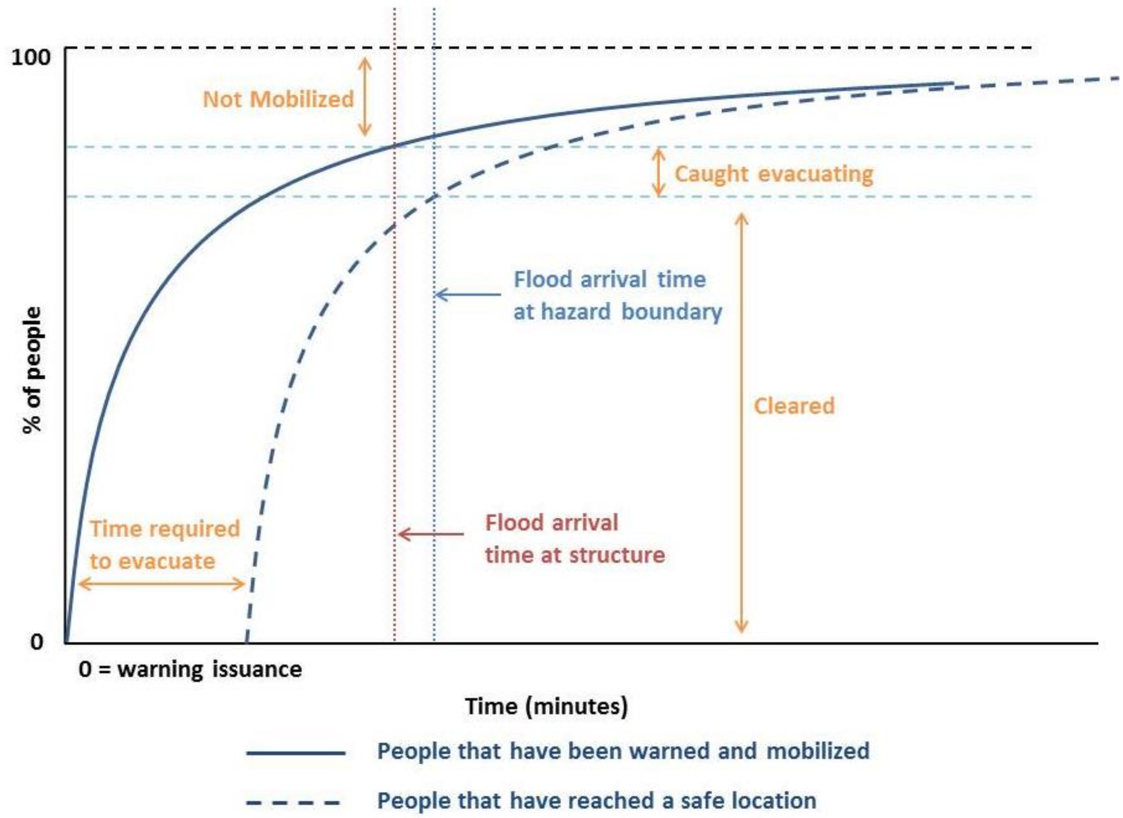

Figure 2.3. Recreated graphic showing assignment of evacuation outcome categories for HEC-FIA/simplified LIFEsim. (Lehman & Needham n.d.)

As each cell in the simulation area reaches the no-evacuation water depth, HEC-FIA assigns the lethality zone and fatality rate for the trapped population. The three lethality zones possible are (Lehman & Needham n.d.):

1. Chance zone: The chance zone is characterized by conditions leading to people being swept away or trapped underwater. In these conditions survival depends on chance (encountering debris to cling to or aid in escape). The historic fatality rate ranges between 38 and 100%. HEC-FIA uses a 91% fatality rate.

2. Compromised zone: In the compromised zone shelters are severely damaged and provide limited protection to people from flood waters. The historic fatality rate under these conditions ranges from 0 to 50%. HEC-FIA uses 12% fatality rate.

3. Safe zone: Flooding in the safe zone is shallow and unlikely to impede on-foot movement. Safe zone fatality rate in HEC-FIA is 0.02%.

Individuals that have not mobilized when the non-evacuation condition is met are assigned a lethality zone based on maximum flooding at the building location, inhabitant age (older inhabitants cannot reach higher areas in the structure) and structure height. It is assumed that the non-mobilized population evacuates to one level above the highest habitable space. (Lehman & Needham n.d.) The maximum product of velocity and depth (dv) is used to describe maximum flooding (USACE 2015). To determine the level of damage to a structure due to maximum dv, HEC-FIA relies on damage thresholds established by RESCDAM (2000). The RESCDAM study synthesizes previous studies to establish the dv values at which different building types (wood framed anchored and unanchored and masonry, concrete, brick structures) suffer partial or total damage (Karvonen et al. 2000). Any individuals caught evacuating are assigned to the chance lethality zone. The corresponding fatality rate is applied to the population remaining in each lethality zone to estimate casualties from the flood event. (Lehman & Needham n.d.)

Shortcomings of HEC-FIA stem mainly from the simplifications used to make the model fast and inexpensive to apply. The lack of a dynamic traffic model and reliance on built-in damage, warning, and mobilization curves introduces uncertainty into the fatality estimates, as some populations may deviate from those used to develop these curves. HEC-FIA also allows for the user to modify all built-in information and evacuation velocity and time. The combination of in-built parameters and flexibility in terms of allowing user defined inputs makes HEC-FIA suitable for estimating fatalities from a GLOF in the high data case (Peru).

Life Safety Model

The Life Safety Model (LSM) is one of the most advanced dynamic flood casualty models available. This model simulates how receptors (term for people, buildings, and vehicles) interact with the flood hazard. BC Hydro, the British Columbia electric utility, initially developed the LSM as a tool to provide credible fatality estimates for dam risk assessment and simulations that would help improve emergency response and planning in the event of a dam failure. In 2004 BC Hydro established a research and development agreement with HR Wallingford, a UK based civil engineering firm, to continue work on LSM. Other agencies and universities also contribute development of LSM including USBUREC, Technical University of Delft, and the University of British Columbia. (Lumbroso et al. 2011)

LSM is unique because of the detailed way in which it assesses the interactions of receptors and flood waters and its reliance on fundamental physics equations to predict the consequences. This level of detail also requires extensive data inputs to develop an accurate initial state of the flood zone including the location of vehicles, inhabitants, buildings, and their characteristics. Input data required includes the location and number of receptors defined as individuals, groups, building types, vehicles, roads, safe havens and warning centers in the region. Additionally the user must provide the results of a two-dimensional model of the flood including water depth and velocity at 15 or 30 second intervals (Lumbroso, Personal Communication, 2014). With this data the LSM models the time dependent flood characteristics and how people (or groups of people) will fare in flood waters given water depth, velocity and flood duration. People can evacuate via pedestrian routes or in vehicles to user defined refuges. A simple traffic model is employed to understand vehicle movement during a flood event; the model also simulates how a vehicle will interact with flood water (stalling, entrainment in flood waters, no effect). In addition, the model assesses how buildings will be affected by the flood. All receptor damage functions are based on the receptor's ability to withstand impact from flood waters characterized by depth and velocity. (Lumbroso et al. 2011)

The complex interaction of individuals and the flood hazard is governed by user specified parameters that include how an individual is warned of the flood, the time it takes for an individual to become aware of the event, actions after an individual becomes aware of the flood (evacuate or remain in place), method of evacuation, and resistance to flood water flow. (Lumbroso et al. 2011)

LSM was used to recreate the failure of Malpasset Dam in France (1959) and showed good agreement with the fatalities reported for this event (Lumbroso et al. 2011). An earlier recreation of the 1953 Canvey Island Flood (conducted in 2008) showed good agreement when considering drowning deaths, but an overestimation of deaths due to collapsing buildings. The researchers attributed this discrepancy to the LSM's calibration for wood framed buildings (typical in the US and Canada), which differs from the masonry buildings more common in the UK, where Canvey Island is located. (Di Mauro & Lumbroso 2008)

LSM's reliance on physics to predict how receptors will interact with flood waters produces detailed and defensible results. Nonetheless, for the results to be valid, the user must possess highly detailed demographic data for the flood region. In addition, various scenarios to represent how people relocate during the day, week, and time of year must be evaluated. Despite the high level of detail, this model is inadequate for estimating damages from either the high or low data cases used in this study. LSM requires far more detailed demographic and flood prediction data than is available at either site.

Structure Damage

The dynamic life loss model used for the high data case (HEC-FIA) estimates structure damage in addition to fatalities. The procedure for determining structure damage in HEC-FIA is described above and is sufficiently flexible for application use in this analysis.

At the Nepal site a building and infrastructure inventory was developed from satellite images of the flood path and confirmed in a field survey. It is assumed that buildings will be irreparably damaged in the event of a GLOF to estimate direct economic losses. This approach, assuming total destruction of structures in the path of the flood, is justified by the high water velocities typical of a dam failure and GLOF event (USDHS 2011a). Infrastructure in the path of a GLOF is also assumed to be severely damaged in the event of a flood.

Vulnerability Assessment

Vulnerability constitutes the human component of risk and is a crucial part of disaster planning and management (Anderson 2000). In particular, vulnerability is a measure of the overall harm to individuals and society resulting from a damaging event (the hazard) (Adger 2006; Balica 2012). Researchers have broken vulnerability down into the physical and social characteristics that affect how an individual copes with a hazard. Physical vulnerability refers to exposure to a hazardous event (Hegglin & Huggel 2008; Chambers 2006). Hegglin and Huggel (2008) find that for a GLOF physical vulnerability depends on outburst probability, flood magnitude, trajectory, and population at risk. In contrast, social vulnerability refers to an individual's susceptibility to and ability to cope with the disturbance produced by a hazard (Chambers 2006; Cutter et al. 2003), which Hegglin and Huggel identify as composed of flood response, prevention, and preparedness (Hegglin & Huggel 2008). Physical vulnerability in this study is addressed via the consequence estimation and scenario analysis steps of the GLOF risk management methodology. Social vulnerability, though, cannot be measured directly because it is an abstract concept. Although Hegglin and Huggel as well as other researchers have addressed social vulnerability via qualitative measures, other studies have developed vulnerability indices to quantify social vulnerability. For this work social vulnerability is used to provide insight into a community's ability to respond, cope, recover, and adapt to a hazard (Cutter et al. 2003). Vulnerability is only quantified for the high data (Peru) site due to the availability of detailed, city-bock level demographic information. Similar data is not available at the Nepal site.

Given the impossibility of directly measuring vulnerability, the quantification of vulnerability relies on proxy measures or indicators, which are aggregated into a vulnerability index. The use of proxy measures for vulnerability is further complicated because of the difficulty of validating the indicators and index. Measures of vulnerability, such as mortality, are imperfect proxies for vulnerability and there is no consensus in the literature of an appropriate proxy for vulnerability (Gall, 2007). However, Schmidtlein et al. (2008) concluded that the best method of validating social vulnerability index results is to compare index results to local knowledge of vulnerability. Despite the difficulties of validating and defining vulnerability indicators and indices they provide important, concise, and actionable information for decision makers and community members alike. Vulnerability indices allow for comparisons across different regions or communities and highlight how limited funds may best be allocated to vulnerable populations (Schmidtlein et al. 2008). In addition, vulnerability indices are already used in Peru as part of the country's disaster planning protocol (INDECI 2003).

Quantitative vulnerability indices are a prominent tool in the literature to assess vulnerability (Balica et al. 2012; Hegglin & Huggel 2008; Cutter et al. 2003; Schmidtlein et al. 2008; Cutter et al. 2006; Borden et al. 2007; Eriksen & Kelly 2006; Urothody & Larsen 2006). In order to draw from the extensive research and knowledge of vulnerability researchers, vulnerability for this study will be quantified using the Cutter et al. (2003) method with adjustments to account for available data and the local concept of vulnerability. Although many quantitative social vulnerability indices exist, we will use the SoVI developed by Cutter et al. because of its flexibility in terms of indicator definition, derivation from a wide array of literature sources, and scale of application. The flexibility of the Cutter et al. approach allows for the use of census data for Huaraz and vulnerability estimation at the city block scale (the resolution of the census data).

Cutter et al. (2003) identified the most often cited characteristics that affect social vulnerability from the literature. In total, Cutter et al. (2003) identified seventeen characteristics listed in Table 2.2. They then defined and tested indicators for each characteristic to define independent, representative indicators using factor analysis and county level US census data. (Cutter et al. 2003)

Table 2.2. List of characteristics affecting social vulnerability and their effect. Adapted from Cutter et al., 2003.

Category	Effect on Vulnerability
Socioeconomic status	High status: mixed Low income or status: increases
Gender	Female: increases
Race and ethnicity	Non-white: increases Non-Anglo: increases
Age	Elderly: increases Children: increases
Commercial and industrial development	High density: increases High value: mixed
Employment loss	Employment loss due to disaster & unemployment: increases
Rural/urban (pop. density)	Rural: increases Urban (high density): increases
Residential property	Mobile homes: increases
Infrastructure and lifelines	Infrastructure affected by disaster: increases
Renters/property ownership	Renters: increases
Occupation	Professional/managerial: decreases Clerical or laborer: increases Service sector: increases
Family structure	High birth rates: increases Large families: increases Single parent: increases
Education	Little education: increases High education: decreases
Population growth	Rapid growth: increases
Medical services	Higher medical density: decreases
Social dependence	High dependence: increases Low dependence: decreases
Special needs population	Large special needs pop.: increases

The Cutter et al. (2003) method established an algorithm for calculating social vulnerability that Schmidtlein et al. (2008) summarize as:

1. Normalize and center all input indicators using z scores (mean of zero and standard deviation of 1) defined in Equation 2.2.

$$zscore = \frac{x_n - x_{n,avg}}{x_{n,stdev}} \tag{2.2}$$

2. Use indicator z scores to conduct a principal component analysis (PCA).

3. Select the number of principal components that best represent the data according to accepted norms for PCA.

4. Optional: rotate PCA solution.

5. Interpret resulting components and determine if they add (positive sign) or subtract (negative sign) from social vulnerability. Assign positive or negative sign to each component as appropriate.

6. Decide on a weighting scheme to aggregate scores into the vulnerability index and implement for the data set.

7. Normalize final vulnerability index to have mean zero and standard deviation of 1.

The Cutter et al. (2003) method (termed SoVI) provides a flexible framework for vulnerability index definition that can be applied to the Peruvian census data to determine the social vulnerability of inhabitants in the path of a GLOF. This framework, however, requires the analyst to make arbitrary judgements in steps 3, 4, and 6 in addition to making arbitrary judgements in how to define the indicators identified in Table 2.4. Schmidtlein et al. (2008) found that the choices made for these steps (3, 4, and 6) can alter the final vulnerability index significantly, in some cases. Therefore Schmidtlein et al. (2008) recommend validating vulnerability index results by relying on expert guidance.

Two independent vulnerability assessments for Huaraz exist and are compared to the vulnerability index developed here. The first was conducted by the Government of Peru (abbreviated as Peru) in 2003 and the second by Hegglin and Huggel in 2008. Both the Peruvian and Hegglin and Huggel studies produced city sector level vulnerability results using qualitative scoring of social vulnerability.

The Peruvian government defines vulnerability as the ease with which an element will suffer human or material damages from a hazard event (INDECI 2006). The Huaraz city vulnerability assessment uses five categories to determine vulnerability (INDECI 2003), as indicated in Table 2.3.

Table 2.3. Categories of Huaraz vulnerability assessment conducted by the Peruvian government (INDECI 2003).

Category	Sub categories	Notes
Human settlements	Population density	Measured in population/hectare
	Systems, materials, and state of buildings	
	Socio-economic level	
Life lines and vital services	Life lines	Potable water, electric services, communication, sewage, transit access
	Vital services	Health and safety services
Economic activity	Centers of economic activity	Central to a return to normal activity in the city
Public concentration	Public spaces	High concentration areas are vulnerable
Historical locations	Historic patrimony	Important for cultural continuity

The Peruvian vulnerability assessment divides the city into eight sectors. Each sector is given an average score for the subcategories listed in Table 2.3 (Population density is the only subcategory that is quantified). Scores for each sector are combined to determine a vulnerability level of very high, high, medium or low. Exactly how the scores are determined and combined is unclear in the assessment report. The resulting vulnerability map is shown in Figure 2.4.

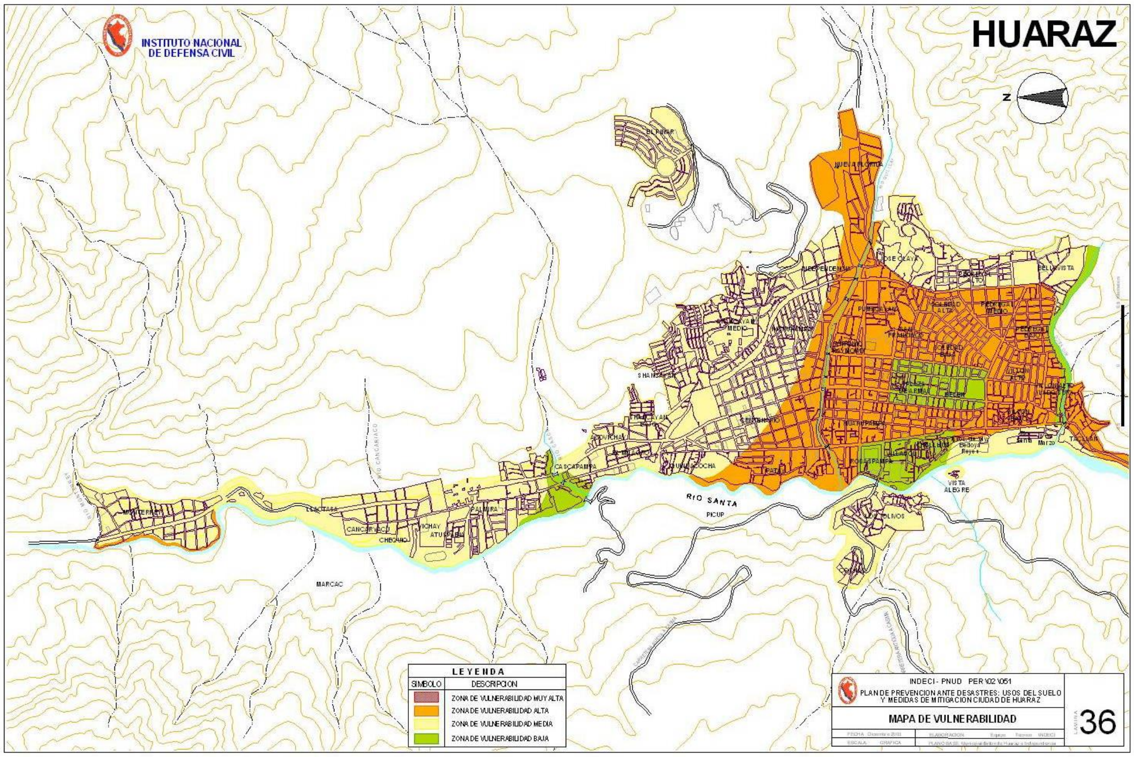

Figure 2.4. Peruvian government vulnerability map for Huaraz City (INDECI 2003). In this map the color green indicates very low vulnerability, yellow indicates medium vulnerability, and orange indicates high vulnerability.

The second vulnerability assessment for Huaraz includes both a physical and social vulnerability component. Physical vulnerability, for the Hegglin & Huggel study, refers to a community's exposure to a hazard event whereas social vulnerability refers to the individual's socioeconomic conditions that affect their ability to withstand a hazard. The social vulnerability results of the Hegglinn & Huggel work are the focus for this study. Table 2.4 contains the categories and subcategories considered for the Hegglin & Huggel vulnerability assessment. (Hegglin & Huggel 2008)

Table 2.4. Categories included in the Hegglin & Huggel (2008) social vulnerability assessment.

Category	Sub categories	Notes
Response	Rescue	
	Reconstruction	
Prevention	Constructional measures	Projects to prevent a hazard in and around the river
	Urban planning	
Preparedness	State organized	includes early warning system, emergency plans, insurance
	Individually entailed	includes awareness, poverty, age

Similar to the Peruvian study, Hegglin & Huggel divide the city into sectors (corresponding to neighborhoods) and assign a score to each vulnerability category. The score is numerical and indicates a low, medium or high value for each sub category. The category values were determined through data (age and poverty), observation of the current situation, and expert elicitation (response category and subcategories). Figure 2.5 shows the social vulnerability map constructed in the Hegglin & Huggel study.

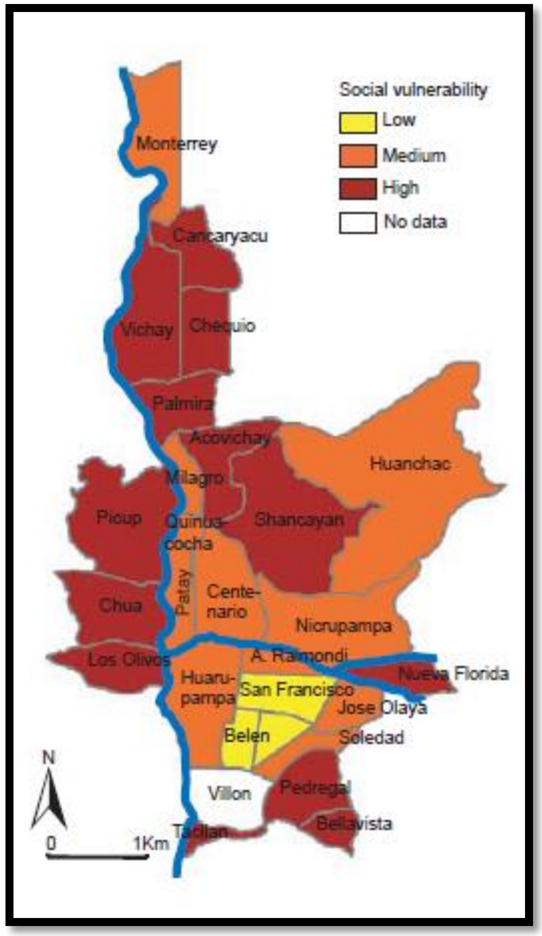

Figure 2.5. Social vulnerability map from the Hegglin & Huggel study.

Since the publication of these two studies, the Peruvian government has conducted a census in 2007 with resolution at the city block level. The census data allows for a higher resolution vulnerability assessment based on quantitative demographic information as well as the development of more indicators, which provide a richer picture of the characteristics of at risk populations to assist in decision making. These data were used in a third vulnerability assessment conducted by a member of the author's research group in 2014. The 2014 vulnerability assessment was conducted using the SoVI methodology as well. (Somos-Valenzuela 2014) However, the 2014 assessment used different indicators, definitions for vulnerability indicators and individual methods to conduct the vulnerability assessment. In particular, the 2014 study used raw data in the census whereas the current analysis aggregates census data into indicators that reflect characteristics that contribute to social vulnerability. This work also develops vulnerability indicators that are GLOF specific and reflect the local definition of vulnerability. Similar GLOF and location specific indicators were not used in the 2014 study.

Although vulnerability indices have no physical meaning and cannot be verified (Gall 2007), they convey the characteristics that make a community susceptible to harm from a GLOF and what actions may reduce the social damage from a potential flood (Balica et al. 2012; Eriksen & Kelly 2006; Schmidtlein et al. 2008). The SoVI (and other indicators) allows for comparison of vulnerability across a community or geographic area, even though the indicator's absolute value has no meaning (Cutter, S L and Finch 2008). Given the SoVI's intangible definition, it will be included in the DEA portion of the economic analysis as described below.

At present there is insufficient data from the Nepal site to implement the vulnerability index methodology. The omission of social vulnerability will have a minor effect on the implementation of the decision methodology given that the main consequences of a flood event, fatalities and direct economic losses (USDHS 2011b), will be estimated.

ECONOMIC ANALYSIS

To frame the adaptation project decision in economic terms the Data Envelopement Analysis (DEA) (Womer et al. 2006; Kortelainen & Kuosmanen 2004) and decision analysis (DA) methodologies are used (Keeney 1982; Ang & Tang 1984). Both methodologies have different advantages and means of comparing risk mitigation proposals that complement each other. DEA allows for the intangible consequences of a project to be compared with market valued costs to understand which project is most efficient in terms of the tradeoff of costs and benefits. In contrast, DA includes uncertainty in the timing and characteristics of a GLOF event to estimate the expected value of a project given existing knowledge about its likelihood and consequences. The information from both methodologies fills knowledge gaps in the decision making process and allows for the inclusion of nuances that may have value to community members. Therefore the DEA methodology is used first to identify inefficient mitigation options taking into account intangible consequences. Results from the DEA methodology will also provide an estimate for the price range of intangibles that favor each project. The DA method is used afterwards to identify the lowest expected cost decision taking into account uncertainty in the timing, occurrence and characteristics of a GLOF.

Data Envelopment Analysis

Data Envelopment Analysis (DEA) is a methodology originally developed in operations research to distinguish efficient options from a set of operating units (Womer et al., 2006). Researchers have adapted the methodology to replace traditional cost benefit analysis (CBA) and address the shortcomings of the traditional methodology (Womer et al. 2006; Kuosmanen & Kortelainen 2004). In particular DEA allows for the comparison of consequences that do not have a market value (such as fatalities and social vulnerability) and for the inclusion of conflicting perspectives on what is a cost or benefit (Womer et al. 2006). DEA does so by reversing the question posed in a traditional CBA and essentially asking what values for costs and benefits are required to make a given project economically efficient (Kuosmanen & Kortelainen 2004). In the Womer approach (abbreviated as the competitive equilibrium method) this is done by aggregating the benefits and costs of the proposed projects in an attribute matrix (w) and maximizing the sum of the costs and benefits for a given project (w*, an array) multiplied by prices/weights (p), which are determined in the maximization shown in Equation 2.3.

$$Max_p p(w*) \tag{2.3a}$$

$$s.t. p(w) \leq 0 \tag{2.3b}$$

$$p^i = 1 \tag{2.3c}$$

$$p \leq a \tag{2.3d}$$

$$p \geq b \tag{2.3e}$$

In the above equation, p^i is used as a numeraire (normalizing price/weight) to avoid the trivial solution, p=0. The terms a and b are used as upper and lower bounds on the weights. If the price for a given effect is positive, then it is counted as a benefit. A negative price indicates a cost. Effects may change from benefit to cost depending on the constituency assigning prices to each effect. (Womer et al. 2006) The method in Equation 2.3 maximizes social benefit with the condition that no project produce a 'profit' ($p(w)\leq 0$). The first constraint (Eq. 2b) in the DEA formulation establishes that the optimal weight vector is one that prevails in a perfect, competitive market (Womer et al. 2006). In other words, the price vector must be such that no firm makes a profit in the 'market' of proposed projects. If an optimized project has a value less than zero (weight times effects gives the value), then the project is not competitive in the project 'market', and is not economically efficient.

Other authors have proposed a second CBA DEA methodology based on each project's competitive advantage as compared to the next best project. The competitive advantage methodology was developed by Kuosmanen and Kortelainen and takes a game theory approach to deriving the weights associated with each impact of a project. This methodology seeks to find the weights that an advocate of a given project would use to maximize the competitive advantage of each project over its closest competitor subject to the project having a positive net social benefit. (Kuosmanen & Kortelainen, 2007) Equation 2.4 contains a description of the methodology.

$$\max_{\mathrm{p}} \mathrm{CA_k} \tag{2.4a}$$

$$\text{s.t.}\ \mathrm{CA_k} \leq \left[\mathrm{B_k} + \sum_{m=1}^{M} \mathrm{p_m Z_{km}}\right] - \left[\mathrm{B_i} + \sum_{m=1}^{M} \mathrm{p_m Z_{im}}\right]$$
$$\text{for } \mathrm{i} = 1, \dots, \mathrm{k}-1, \mathrm{k}+1, \dots, \mathrm{N} \tag{2.4b}$$

$$\mathrm{B_k} + \sum_{m=1}^{M} \mathrm{p_m z_{km}} \geq 0 \tag{2.4c}$$

$$\mathrm{p} \geq 0 \tag{2.4d}$$

$$\text{Where: } \mathrm{CA_k} = \left[\mathrm{B_k} + \sum_{m=1}^{M} \mathrm{p_m Z_{km}}\right] - \left[\mathrm{B_n} + \sum_{m=1}^{M} \mathrm{p_m Z_{nm}}\right] \tag{2.4e}$$

In Equation 2.4 the subscript k refers to the project whose competitive advantage is being maximized and n refers to the project that has the lowest value compared to k. The monetary benefits or costs of the project and competitors (subscript i) are aggregated into the B term in the first constraint. Each non-market cost or benefit is represented as Z_m and multiplied by the corresponding price (p_m). The difference of monetary and non-market benefits and costs for the target project and other projects must be less than or equal to the maximized competitive advantage. Therefore project k is compared to the best competitor, project *n* in Equation 2.4e (Kuosmanen & Kortelainen 2004). In addition the net benefits of the target project must be positive as should the weights themselves (p_m). The competitive equilibrium method is the same as the competitive advantage method when the competitive advantage of k (as compared to any project) is less than or equal to zero. Nonetheless, the competitive advantage method is a closer approximation to the traditional cost benefit methodology which seeks to identify the project with the maximum net benefits.

The outcome of the DEA methodology is a series of 'price' vectors (these are not market prices, rather optimized weights for each project) specifying the weight of each impact (benefits and costs) that maximizes social benefit or a project's competitive advantage depending on the methodology used. The price vectors give important information as to how well each alternative 'scores' for each impact. A low price for a given impact indicates that project advocates assign it a low value. The resulting price vectors can be compared to stakeholder opinions on the various effects under consideration (does effect x, particularly valuable to community members have a high price in project y's price vector?). These prices also indicate which constituency will suffer harm or reap benefits from a given proposal. In addition, the analyst can use the DEA framework to determine over what range of prices a given project is the best decision from an economic standpoint (Kuosmanen & Kortelainen 2004). Another benefit of the DEA methodology is that it avoids differences in opinion over whether a given effect is a benefit or cost. Effects that are strictly considered to be benefits will be constrained to have a positive value, whereas the price of costs will be constrained to a value less than zero. Ambiguous effects can remain unconstrained. Because of the many stakeholders in the decision making process, allowing for different prices and evaluating the robustness of various projects allows for consensus building among stakeholders around a single project. (Womer et al. 2006)

Decision Analysis

In contrast to DEA, decision analysis (DA) allows for inclusion of uncertainty in the timing and characteristics of a GLOF event. DEA, as structured here, compares the present value of costs and benefits for one GLOF scenario at a time. Although a sensitivity analysis can be conducted to understand how the efficient alternative changes with time to a flood, the uncertainty surrounding the timing and characteristics of a GLOF cannot be included in the analysis. Given that the occurrence in time of a GLOF and characteristics of the event cannot be known deterministically, this analysis relies on DA to reflect these probabilistic variables.

DA is a normative methodology for systematically assessing the complex components of a decision problem (Keeney 1982). In decision analysis an expected value, monetary or utility, for each decision is calculated and compared to other alternatives (Ang & Tang 1984; Keeney 1982). The methodology consists of listing the feasible alternatives to resolve the decision problem, the outcome of each alternative, and the probability of each outcome. Next the analyst must quantify the consequences of each alternative and outcome possible, establish a criteria for the decision, and conduct a systematic evaluation of each alternative given the previous information (Ang & Tang 1984). Outcomes and probabilities may be expressed as a distribution or discrete values.

Although a GLOF event's extent can be predicted, the probability of an event occurring in time or likelihood that it will match one of the scenarios in Figure 2.4 cannot be known due to the complex interaction of physical processes that lead to a GLOF event. The uncertainty regarding the probability ascribed to each branch of the GLOF decision tree can be reflected by using a diffuse prior distribution as shown in Figure 2.6. Time to a GLOF event is also unknown and is considered as a uniform distribution ranging from zero years (flood in the present) to the lifetime of the adaptation project.

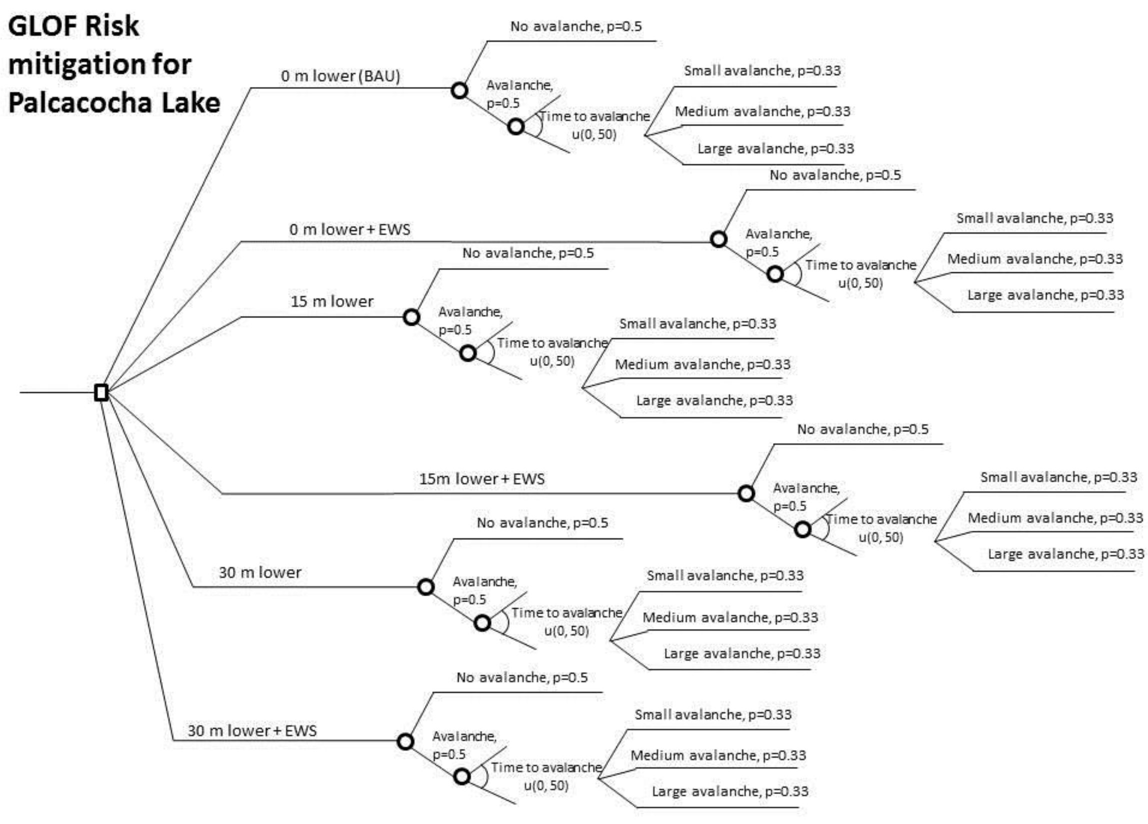

Figure 2.6. Example of a decision tree used for the decision analysis methodology. Equal probability is ascribed to each branch to reflect the lack of knowledge about the likelihood of each alternative.

Each branch exiting the rectangle at the left of the decision tree represents a decision. The expected value of the decision is calculated by multiplying the cost of consequences for each branch by the probability of its occurrence. Unlike DEA, DA requires the analyst to place a value (economic or utility) on intangible consequences. The best decision is the one with the greatest expected value (or lowest expected costs). By comparing expected values, the result incorporates the unavoidable uncertainty in GLOF prediction as well as the results of previous research and analysis to understand the conditions at Imja and Palcacocha lakes.

Given the limited information on the probability of a GLOF a sensitivity analysis will also be conducted to understand the threshold for a change in the lowest cost decision from the DA methodology. The value of the decision tree variables (probabilities and time to a GLOF) as well as the value of intangibles and the discount rate are assessed in the sensitivity analysis. Although the sensitivity analysis used here differs from the traditional sensitivity analysis (small perturbation of uncertain variables), the objective is to determine whether the best decision is robust to changes in the highly uncertain variables (Lempert 2003).

Chapter 3: Imja Lake Lowering Analysis

INTRODUCTION

In this chapter the decision making methodology is applied to Imja Lake in Nepal. Imja Lake is located in the Khumbu region of Nepal close to the Nepalese border with Tibet (27°53’53” N, 86°55’41” E) and on one of the most popular trekking routes to Mt. Everest (Fujita et al. 2009) as shown in Figure 3.1. The Lhotse Shar, Imja, and Amphulapcha glaciers contribute to Imja Lake, which is part of the Imja Khola watershed. Outflow from Imja Lake drains to the Imja Khola river (Somos-Valenzuela et al. 2015), which is a tributary of the Dudh Khosi. (ICIMOD 2011)

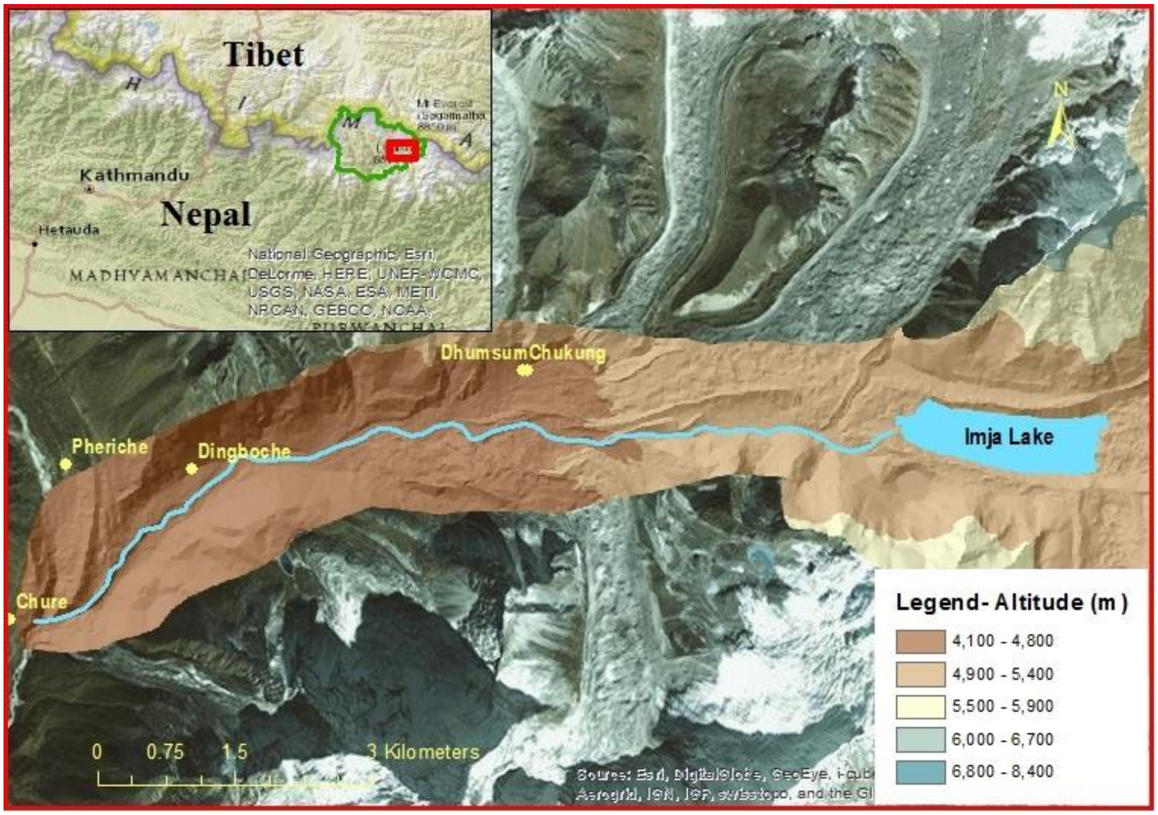

Figure 3.1. Map of Imja Lake and downstream communities in the Khumbu region of the Himalaya, Nepal.

In the 1950s, Imja Lake was a collection of melt ponds on the surface of Imja glacier. By 1984, however, the lake measured approximately 0.4 km^2 and had grown to over 1 km^2 in 2011 (ICIMOD 2013; Kattelmann 2003). Although Imja's growth has slowed recently, its rapid rate of growth, physical characteristics, and possible moraine instability have raised concern that the lake poses a high potential for an outburst flood (Ives et al. 2010; Kattelmann 2003; Somos-Valenzuela et al. 2015; ICIMOD 2011) that will only increase with time (Rounce et al. 2016). Nonetheless, several studies have also found that the potential for a GLOF from Imja Lake is lower than previously thought. (Fujita et al. 2009; Watanabe et al. 2009; Hambrey et al. 2008) Despite the disagreement over the danger posed by Imja lake, researchers have conducted numerous studies to understand how a GLOF from the lake would affect areas downstream (ICIMOD 2011; Rounce et al. 2016; Somos-Valenzuela et al. 2015). Other studies of the lake have also focused on lake characteristics (Somos-Valenzuela et al. 2014), moraine and glacier characteristics (Hambrey et al. 2008), and melting of source glaciers (Rounce et al. 2015). Recent field studies of the lake have found water seeping through the moraine and studies of satellite imagery show that the lake continues to grow toward the source glacier (Somos-Valenzuela et al. 2015; Watanabe et al. 2009; Rounce et al. 2016), which raises concern about the lake's safety.

Although GLOF mitigation works have been conducted at lakes in Nepal previously (ICIMOD, 2011; Rana et al., 2000) and are funded for Imja Lake (UNDP 2013), these decisions have not been made by rigorously assessing the change in flood damage resulting from mitigation works. Discussions surrounding projects for Imja have not included a detailed analysis of the potential consequences of a flood, probability of an event, or costs of mitigation projects in part because this information is unknown and uncertain. GLOF risk mitigation strategies usually consist of draining water from the glacial lakes and lowering the lake level. By lowering the lake level pressure on the moraine will decrease and the surge of water flowing downstream will be less in the event of a flood, resulting in a smaller inundation area. At present the government is accepting bids to lower the level of Imja Lake by 3 meters (CEPAD 2015; CEPTE 2012; UNDP 2013). This is the preferred method of GLOF mitigation as it does not require maintenance and allows the community to retain its current location and practices (ICIMOD, 2011).

In this chapter the GLOF decision making framework is applied to Imja Lake, a low data case, and projects to lower the lake by up to 20 meters. Imja Lake is considered to be a low data case due to the lack of census, demographic, or infrastructure inventory data for communities downstream of the lake.

IMJA LAKE ANALYSIS

Despite limited data available for Imja Lake, the objectives for this analysis are to identify likely GLOF scenarios and mitigation projects, estimate damage from a potential GLOF to people and infrastructure with and without mitigation measures, identify economically efficient mitigation projects taking into account intangible damages from a GLOF, and to identify the least expected cost project taking into account uncertainty in the timing and occurrence of a GLOF. The analysis consists of first identifying likely GLOF and lake lowering scenarios. Next, the consequences of each flood and lake lowering scenario are estimated using field and satellite data to fill knowledge gaps. The first step of the economic analysis is to use consequence data in the data envelopement analysis (DEA) methodology to identify efficient projects. Next \a decision analysis of the lake lowering projects is conducted to identify the least cost option. The analysis conducted here will conclude which is the best project from an economic standpoint taking into account the limited data and uncertainty surrounding a GLOF from Imja Lake.

Scenario Analysis

The first step of the Imja Lake analysis is to identify potential GLOF scenarios and mitigation projects. Water seepage through the terminal moraine has been observed during recent visits to the lake (Somos-Valenzuela et al. 2015). Additionally, ground penetrating radar and electrical resistivity tomography studies have identified dead ice in the lake's terminal moraine, which can melt as temperatures rise and cause instability (Fujita et al. 2009; Hambrey et al. 2008; Somos-Valenzuela et al. 2012). The observed seepage indicates piping of water through the moraine and also instability of the terminal moraine. These two features suggest that a likely GLOF trigger at Imja Lake is moraine failure. Given that the lake is significantly removed from surrounding steep slopes and therefore unlikely to experience a GLOF due to an avalanche induced wave, the moraine collapse failure mode is the only GLOF trigger considered in this analysis. Recent work has determined that the lake will be at risk for a rockfall or avalanche into the lake in 10 to 20 years (Rounce et al. 2016). Given the lack of information on the consequences of a mass movement into the lake, such an event is not considered here.

For this analysis model results from flood due to moraine failure at Imja Lake with and without a flood mitigation project are used here. A no lake lowering decision is termed business as usual (BAU) since no change is made to the lake. As mentioned previously, lake lowering is the preferred flood mitigation action. GLOF mitigation works included here are 3 meter (current proposal (UNDP 2013)), 10 meter, and 20 meter lake lowering. At 10 meters previous modelling shows a significant decrease in damage to the downstream community of Dingboche. Lowering the lake by 20 meters nearly eliminates damage in Dingboche. (Somos-Valenzuela et al. 2015)

Figure 3.2. Map of Imja Lake (Tsho), nearby villages, trekking path, and predicted depth of a GLOF with no lake lowering works. Map shows extent of GLOF modelling.

Modelling of the flood scenarios analyzed here was previously conducted by Somos-Valenzuela et al. in 2015. This modelling was conducted by Somos-Valenzuela using HEC-RAS to simulate moraine failure and FLO-2D to simulate water flow in the valley downstream as discussed in the methods chapter (Chapter 2). Results from the modelling in the form of maximum depth and depth times velocity (d*v) rasters were kindly provided by Marcelo Somos-Valenzuela for this analysis. Figure 3.2 contains a sample of the modelling results used for this analysis. The results simulate approximately 38.5 km of flooded area downstream from the outlet of Imja Lake due to limitations of the available DEMs at the time of modelling. In the modelled area downstream of Imja Lake only one village, Dingboche, would experience inundation from a GLOF. (Somos-Valenzuela et al. 2015)

Consequence Estimation

For this analysis direct damage from a GLOF to homes and buildings, agriculture land, the Dingboche-Chhukhung and Chhukhung-Imja trekking path, and to people in Dingboche was considered. Indirect economic damages and valuation of damage to property other than structures was not considered here because of a lack of data and because a detailed assessment of the rural Nepal economy is outside the scope of this work. In addition to consequences of a flood, the cost of implementing the various flood mitigation projects considered here was also estimated. Data for consequence estimation was gathered through field surveys, literature sources, and analysis of satellite imagery.

Combining the property and population surveys with flood modelling results and fatality estimation techniques the damage from a potential GLOF from Imja Lake with and without adaptation measures is estimated. Table 3.1 summarizes the results of the consequence estimation methodology which is described in detail in the following sections.

Table 3.1. Results of GLOF consequence estimation for damages to people and infrastructure.

	Fatalities, high season	Fatalities, low season	Homes damaged	Ag. land damaged (m^2)	Trail length damaged (km)	Cost of lake lowering (USD)
BAU	3-10	1-2	20	93650	7.97	$0
3m decrease	2-5	0	14	86262	7.85	$2,260,822
10m decrease	0	0	4	40226	7.45	$4,285,496
20m decrease	0	0	1	10686	4.64	$7,768,820

Infrastructure Damage

The building inventory was developed using a combination of satellite imagery and field surveys. Initially satellite imagery from ArcGIS (high resolution World

Imagery) (Digital Globe 2013), Google Earth (Google Earth 2015), and Digital Globe imagery (Digital Globe 2015) was used to identify buildings in the flood plain to survey in the field. Two colleagues, David Rounce and Alton Byers, conducted field surveys to confirm the initial building inventory during a visit to the area in October of 2015. They surveyed a total of 54 points identified in the initial building inventory. The field survey confirmed the presence of a building, identified the type of building (home, shed, etc.), the number of occupants, and whether the building was inhabited seasonally or year round. Figure 3.3 shows a summary of the structures in Dingboche surveyed and Table 3.2 contains a sample of the information gathered about them.

Table 3.2. Sample of 21 points surveyed and data collected during the field visit to Dingboche.

FID	Off Season Inhabitants	High Season Inhabitants	Building Type
0	3	3	Tea house (1.5yrs old)
1	0	0	Storage
2	0	0	Storage
3	0	0	Storage
4	0	0	Storage
5	2	2	Snooker tea house
6	0	0	Storage
7	0	0	Storage
8	0	0	Storage
9	2	2	House
10	20	20	Arizona Lodge
11	0	0	Rock pile
12	2	46	Everest Resort & auxillary rooms
13	0	0	Everest Resort & auxillary rooms
14	0	0	Storage
15	0	0	Camping kitchen connected to hotel
16	0	0	Trash
17	0	0	Storage
18	2	14	House rents to porters
19	0	0	Storage
20	0	3	House, occupied tent on property seasonally

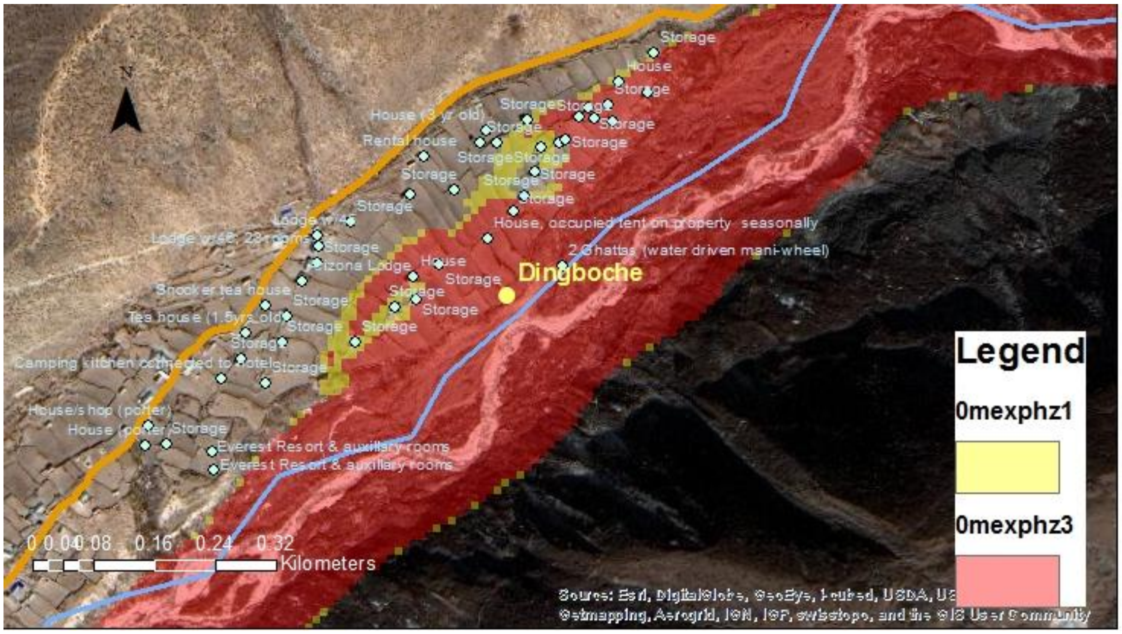

Figure 3.3. Buildings in Dingboche were identified using satellite imagery. The type and inhabitants of each structure was confirmed via field survey. Red (high hazard) and yellow (low hazard) on the map indicates flood hazard with no lake lowering.

In addition to buildings and inhabitants, damage to agricultural land and to the Dingboche-Chhukhung and Chhukhung-Imja trekking path was also considered. Agriculture and tourism are important economic activities in the region (Byers & Thakli 2015). The area of agricultural land in the GLOF flood plain was estimated by colleagues in a 2015 paper (Somos-Valenzuela et al. 2015). The Dingboche-Chukkhung and Chhukhung-Imja trails are part of the series of trails leading to Island Peak, a popular trekking peak near Mt. Everest. The trail location was exported from Google Maps (Google Maps 2016) and from datasets provided by the Sagarmatha National Park for use in this analysis.

Damage to infrastructure is estimated by overlapping the flooded area with the building, agricultural land, and trekking trail maps. It was assumed that if the infrastructure is in the path of flood water it will be damaged. In this analysis the extent of damage is not estimated. Given the limited information about the conditions of infrastructure and its ability to resist flood waters, the level of damage cannot be confidently estimated. The final damage estimate for infrastructure is presented in Table 3.1.

Fatality Estimation

Fatalities are estimated using the empirical method (DSO-99-06) described in the methods section (Chapter 2). This method provides fatality rates depending on the flood severity, warning time and the public's understanding of flood severity (Graham 1999). Given the lack of an emergency warning system for GLOFs at Imja Lake (which corresponds to no warning time in the empirical method and means flood severity understanding is not applicable), the fatality rate depends on the flood severity solely. Graham provides a method for estimating the flood severity depending on d*v, mean annual discharge, and discharge after dam failure. Flood severity is also described qualitatively by the level of damage to buildings. Because Graham's method is not specific to the construction methods in less developed regions of the world, this analysis uses the flood intensity classifications used by Somos-Valenzuela et al. (2015) that were developed by Garcia-Martinez and Lopez after observing the aftermath of debris flows in Venezuela (Garcia-Martinez & Lopez 2007). The damage in each intensity category matches the event intensity damage described by Graham. Table 3.3 shows the maximum depth and d*v characteristics for each intensity level and the damage incurred. As a comparison, the qualitative description of flood severity provided by Graham is included in Table 3.3.

Table 3.3. Debris flow event intensity and flood severity characteristics (adapted from Garcia-Martinez & Lopez, 2007 and Graham, 1999).

Event intensity	Maximum depth in m	d*v in m^2/s	Damage—Garcia-Martinez & Lopez	Damage—Graham
high	d>1.0	OR d*v>1.0	People: In danger inside and outside buildings Buildings: in danger of destruction	High severity: Complete removal of buildings in flood path
medium	0.2 < d< 1.0	AND 0.2< d*v <1.0	People: In danger outside Buildings: damage or destruction depending on construction	Medium severity: Homes and trees mangled
low	0.2 <d <1.0	AND d*v< 0.2	People: low to none Buildings: little damage	Low severity: Buildings not washed off foundations

Using the results of the FLO-2D modelling conducted by Somos-Valenzuela et al. (2015), the area of Dingboche that will experience high, medium and low debris flow intensities according to the characteristics in Table 3.3 was identified. Figure 3.4 shows the results of converting the FLO-2D outputs to flood severity regions identified in Table 3.3.

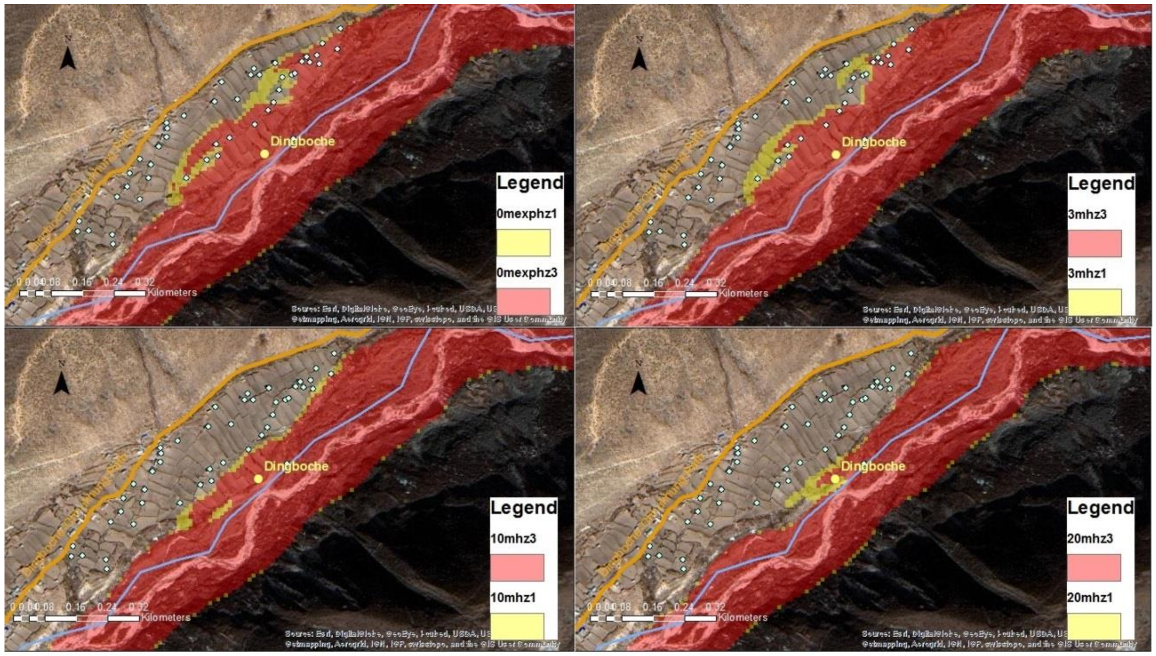

Figure 3.4. Flood intensity regions (high in red and medium in yellow) using flow characteristics in Table 3.2 are shown overlayed with structures identified in Dingboche. Clockwise from top left the images show flood severity for 0 m lowering, 3 m lowering, 10 m lowering, and 20 m lowering.

The flood intensity zones correspond to the qualitatively described flood severity categories Graham uses in his fatality estimation method. Table 3.4 shows a reproduction of an abridged version of the fatality rate table including only the fatality rates applicable to an Imja GLOF (no warning time).

Table 3.4. Abridged table of fatality rates from Graham, 1999.

Flood Severity	Fatality Rate (Fraction of people at risk expected to die)	
	Suggested	Suggested range
High	0.75	0.3 to 1.00
Medium	0.15	0.03 to 0.35
Low	0.01	0.0 to 0.02

Results of the fatality rate estimation using the fatality rate range in Table 3.4 are presented in Table 3.1. Given the use of fatality rates, the DSO-99-06 method does not always result in integer fatalities. Therefore the fatality values are rounded to the nearest whole number. Although the fatality range for each scenario is estimated, for the economic analysis the highest fatality rate is used from the suggested range presented by Graham. The highest fatality rate presents a worst case scenario for flood damages and provides guidance for conservative decision making.

Lake Lowering Cost Estimate

Finally the cost of implementing the lake lowering and moraine reinforcement works described in the Scenario Analysis section is estimated. Because the Government of Nepal (GoN) is currently accepting bids to lower Imja Lake by 3 m, detailed cost estimates for lake lowering works are available. The design report for the lake lowering project at Imja Lake also estimates costs to lower the lake by 5 m (CEPAD 2015). By comparing the cost estimate for each project category to lower the lake 3 and 5 meters, the cost categories that vary with the amount of lake lowering (referred to as 'variable') and those that are independent of the magnitude of the works (referred to as 'one time') can be identified. Table 3.5 contains the cost estimates for each lake lowering option as well as the cost type. Costs were converted from Nepali Rupees to US Dollars (USD) using a conversion rate of 108.70 Rupees equals 1USD.

Table 3.5. Cost estimate for lake lowering works given in USD. (Adapted from CEPAD, 2015)

Item	Cost to lower 3 m	Cost to lower 5 m	Cost type
Civil works	$1,101,163	$1,225,245	variable
Hydro mechanical works	$52,742	$52,742	variable
Logistic and insurance of laborers	$196,830	$223,979	variable
Insurance for works	$14,179	$15,420	variable
Water supply and electricity cost	$38,667	$43,216	variable
Waste management cost	$20,334	$22,727	variable
Health facilities	$76,282	$76,282	one time
Communication	$43,424	$43,424	one time
Heavy equipment transportation	$145,762	$145,762	one time
Construction supervision & management	$199,757	$199,757	one time
Office camps and warehouse	$264,024	$264,024	one time
Sub total	**$2,153,164**	**$2,312,577**	
Contingencies 5%	**$107,658**	**$115,629**	
Total	**$2,260,822**	**$2,428,206**	

To scale the cost of lake lowering works to the 10 and 20 m lowering scenarios, the cost per meter of lake lowering for each variable cost category was calculated using the values in Table 3.5. The cost per meter of lake lowering was lower for the 5 m project than the 3 m project. This difference likely is the result of decreased costs due to economies of scale. Table 3.6 includes the cost per meter of lake lowering for the variable cost types and the two lake lowering projects.

Table 3.6. Cost per meter of lake lowering at Imja Lake for variable cost categories. Costs are given in USD.

Item	Cost per meter to lower 3 m	Cost per meter to lower 5 m
Civil works	$367,054	$245,049
Hydro mechanical works	$17,581	$10,548
Logistic and insurance of laborers	$65,610	$44,796
Insurance for works	$4,726	$3,084
Water supply and electricity cost	$12,889	$8,643
Waste management cost	$6,778	$4,545
Total	**$474,639**	**$316,666**

To estimate the cost to lower the lake 10 and 20 m, the cost per meter to lower the lake 5 m was used and scaled using the number of meters of lowering ($/meter in Table 3.6 multiplied by number of meters of lowering) giving the results shown in Table 3.7. In addition, the contingency category was doubled (10% instead of 5%) to account for the increased uncertainty of extrapolating cost estimates to 10 and 20 m. It is important to note that the values in Table 3.6 are estimates based on much smaller works at the lake (lowering 3 and 5 m). There is no guidance on the cost to lower Imja Lake by 10 and 20 m or how to extrapolate costs from the 3 and 5 m estimates, therefore the estimates in Table 3.6 are highly uncertain and should be reevaluated before undertaking these projects. Table 3.7 summarizes the cost estimates for lowering the lake 10 and 20 m. The cost estimate provided in CEPAD, 2015 was used for the 3 m lake lowering project.

Table 3.7. Results of lake lowering cost estimates for the 10 and 20 m lowering projects.

Item	Cost to lower 10 m	Cost to lower 20 m
Variable costs	$3,166,658	$6,333,315
One time costs	$729,248	$729,248
Subtotal	$3,895,906	$7,062,563
10% contingency	$389,591	$706,256
Total	**$4,285,496**	**$7,768,820**

Economic Analysis

The objective of this work is to develop a rational means of weighing the costs and benefits of the different GLOF mitigation projects proposed. Using the estimates of the consequences of a GLOF given different risk mitigation projects, the consequences of each project can be compared using economic methods and valuation. The objectives for the economic analysis portion of this work are to fill knowledge gaps regarding how to value intangibles and unpriced infrastructure in Dingboche, determine which projects are efficient, and determine which project has the least expected cost. To do so an economic analysis is conducted using the Data Envelopement Methodology (DEA) and Decision Analysis (DA) as an alternative to the traditional Cost Benefit Analysis (CBA).

Data Envelopment Analysis

An alternative method of economic analysis that addresses the shortcomings of traditional cost benefit analysis is Data Envelopment Analysis (DEA). The DEA methodology was first developed for use in efficiency analysis for operations research and has since been applied to cost benefit analysis (Kuosmanen & Kortelainen 2004; Womer et al. 2006) to avoid the controversy and difficulty of assigning prices to non-market (intangible) goods. The goal of this methodology is to identify the most efficient project, from an economic standpoint, if all projects competed in a perfect market. A detailed overview of the two approaches to CBA using DEA is given in the Literature Review chapter. For this analysis the Womer formulation (shown in Equation 3.1) of DEA for CBA was used because of its simpler formulation and similarity to traditional markets.

$$\underset{p}{Max}\ p(w^*) \tag{3.1a}$$

$$s.t. p(w) \leq 0 \tag{3.1b}$$

$$p^i = 1 \tag{3.1c}$$

$$p \leq a \tag{3.1d}$$

$$p \geq b \tag{3.1e}$$

In Equation 3.1 the benefits and costs of the proposed projects are aggregated in an attribute matrix (*w*). The sum of the costs and benefits for a given project (*w**, an array) multiplied by prices/weights (*p*) is maximized given the constraint that no project produce a 'profit' ($p(w) \leq 0$). In the above equation, p^i is used as a numeraire (normalizing weight) to avoid the trivial solution, p=0. The terms a and b are used as upper and lower bounds on the weights to reflect any societal norms. If the price for a given effect is positive then it is counted as a benefit; a negative price indicates a cost.

The DEA methodology works by balancing costs and benefits given market constraints. In the case of a GLOF from Imja lake, the benefit provided by mitigation projects is a decrease in damages as compared to the do nothing (BAU) scenario at the cost of the lake lowering works. Therefore for the DEA relative damage as compared to the BAU case is used instead of the total damage values given in Table 3.1. This formulation eliminates the BAU case from the analysis. Table 3.8 contains the relative benefit estimates used in the DEA.

Table 3.8. Relative benefit estimates used in the DEA.

	Fatalities avoided high season	Fatalities avoided off season	Building damage avoided	Ag. Land damage avoided (m^2)	Trail length damage avoided (km)
3m decrease	5	2	6	7388	0.12
10m decrease	10	2	16	53424	0.52
20m decrease	10	2	19	82964	3.33

The value of building damage can be estimated using home rebuilding estimates from the 2015 earthquake in Nepal. Several organizations and individuals requested donations from the public to rebuild homes in the areas affected by the earthquake. Although none of the requests were specifically for Dingboche, the requests provide an estimate for home construction costs in Nepal. The home cost estimates from a preliminary search ranged from $2,100 for earthquake proof, pre-fabricated homes to $14,200 for an earthquake resistant home for an individual (the request noted that typically a home in the area costs $5,700). Other estimates were in the $2,000 and $5,000 range[1].The lowest cost ($2,100) was averaged with the highest traditional home construction cost ($5,700) to arrive at $3,850 as the cost estimate to rebuild a damaged building. Because most of the structures at risk are actually uninhabited sheds or other structures, the estimate used here is considered a high estimate. Nonetheless, the cost of transporting material to the remote village of Dingboche may justify higher costs for structure construction. The values for cost of building damage in Table 3.9 are given by multiplying the building damage avoided category by the rebuilding cost estimated here

[1] Source: Crowdfunder, Kakani-One house at a time fund; Global Giving Foundation, GoodWeave works; The Fuller Center for Housing; Indiegogo, Rebuild Chhulemu fund

($3,850). Table 3.9 also shows the relative project costs and net benefits for each decision. Net benefits were calculated by subtracting project costs from the cost of avoided building damage (a benefit).

Table 3.9. Project costs were subtracted from the cost of building damage avoided to calculate net benefits of each project.

	Project costs	Cost building damage avoided	Net benefits
3m decrease	$2,260,822	$23,100	-$2,237,722
10m decrease	$4,285,496	$61,600	-$4,223,896
20m decrease	$7,768,820	$73,150	-$7,695,670

The Matlab software and the 'linprog' linear programming tool were used to solve the optimization shown in Equation 3.1. The outcome of the DEA methodology is a series of weight vectors ('prices' for each consequence category) and the value of each project (sum of costs and benefits multiplied by weights). Net benefits are used as the numeraire; net benefits' weights are set to 1 because they are a benefit. Additionally, by assigning net benefits a weight of one, all other weights are in units of dollars. The maximum value possible for a project is zero given the constraints of the DEA methodology shown in Equation 3.1. Projects that do not maximize the cost/benefit equation (have a value of zero) under the problem constraints are not on the efficient frontier in the project 'market'.

The DEA solution is a set of weights that maximizes the value of each project within the DEA constraints; efficient projects have a value of zero. The weight vectors give important information as to how well each alternative 'scores' for each consequence.

A low weight for a given consequence indicates that it contributes little to making the project efficient.

For the problem analyzed here, though, the optimization does not give a unique solution. The problem posed for Imja Lake has too many degrees of freedom (or, too few constraints). For a unique solution to exist the value for at least two more consequence category must be known or additional constraints must be placed on the weight for each variable. The problem has one equations and 3 unknowns when the project is efficient. Therefore, a range of weights exists for each damage category that satisfies the problem constraints. Linprog uses an interior point algorithm and arrives at a solution using an iterative approach similar to the Newton method (MathWorks 2016). Consequently, the algorithm exits when it encounters the first feasible solution because a unique solution for this problem does not exist. The solution reported by Matlab depends on the initial point generated by the algorithm.

Results arrived at by the linprog algorithm for the high and off season scenarios are given in Tables 10 and 11. Projects that achieved a value of zero and are efficient are highlighted in pink. Inefficient projects are crossed out. The DEA methodology does not formally accommodate uncertainty in the timing of a GLOF and therefore fatalities in the high and low season (as noted previously, the high value from the fatality range presented in Table 3.1 is used). Consequently the DEA methodology is conducted for both the high and low season scenarios.

Table 3.10. Results of the DEA methodology for the high season are shown; weights (other than costs) are given in dollars per unit of damage category unit. Highlighted projects are efficient (have a project value of 0) and crossed out projects are inefficient.

Project	Net benefits	Fatalities	Ag. Land (/m^2)	Trail length (/km)	Project value
~~Lower 3 m~~	~~-1~~	~~$422,390~~	~~$0~~	~~$0~~	~~-$125,774~~
Lower 10 m	-1	$155,990	$46	$447,210	$1.79e-07
Lower 20 m	-1	$86,652	$39	$1,070,551	-$2.22e-07

Table 3.11. Results of the DEA methodology for the low season are shown. Highlighted projects are efficient (have a project value of 0).

Project	Net benefits	Fatalities	Ag. Land (/m^2)	Trail length (/km)	Project value
Lower 3 m	-1	$978,360	$27	$657,851	-$4.6e-08
Lower 10 m	-1	$354,176	$62	$342,907	-$1.3e-07
Lower 20 m	-1	$1,016,843	$5.1e-08	$1,700,295	$9.3e-10

Tables 10 and 11 show that in the high season lowering Imja Lake by 10 and 20 meters are efficient projects. Benefits obtained from lowering the lake by 3 meters are insufficient for it to be on the efficient project frontier. In the low season, however, all three lake lowering projects are efficient.

As mentioned previously, the projects analyzed here are efficient under a range of prices. Projects are efficient if the cost benefit ratio or, return on investment for any consequence category is greater than that of another project. The cost benefit ratio is calculated by dividing the absolute value of net benefits (monetary cost of each project) by the benefits provided by each project shown in Table 3.8. The maximum cost benefit ratio for each damage category establishes a benefit production frontier and bounds the weight for each damage category. If the category is assigned a weight greater than this frontier, one of the projects under consideration will have a value greater than zero, which violates the DEA constraints (see Equation 3.1). Table 3.12 shows the cost benefit ratio for the agriculture land category and the corresponding project values when agricultural land is assigned a weight equal to the cost benefit ratio for each lake lowering project. In this example project values are calculated with the weight of all consequences besides agricultural land and net benefits (weight of 1) equal to zero.

Table 3.12. Cost benefit ratios of agricultural land for each project is summarized here as well as the corresponding project value when agricultural land is assigned a value equal to each cost benefit ratio (all other damages are assigned a value of zero).

	Lower 3m	Lower 10m	Lower 20m
Agricultural land cost benefit ratio	\$303	\$79	\$93
Lower 3m project value	\$0	\$11,895,885	\$17,359,814
Lower 10m project value	-\$1,653,599	\$0	-\$1,136,233
Lower 20m project value	-\$1,552,417	\$731,668	\$0

The analysis in Table 3.12 shows that the maximum weight that can be assigned to agricultural land and still fulfill the DEA constraints is \$79. At this constraining weight for agricultural land, the 10 m lake lowering project has a value of zero and the other two projects have a value less than zero, fulfilling the DEA constraints. All other cost benefit ratios proposed in Table 3.9 result in at least one project having a value greater than zero and violate the DEA constraints. Therefore the range of agricultural land damage weights that can result in economic efficiency is zero to \$79. If a similar analysis for the other damage categories is conducted, the results are the constraining weights summarized in Table 3.13. These constraining weights are the upper bound (lower bound is zero) for the range of consequence weights that result in at least one project being efficient.

Table 3.13. Constraining weights summarized here are the maximum weight that can be assigned to each damage category for the projects identified in Tables 7 and 8 to be efficient.

	Fatalities high season	Fatalities off season	Ag. Land (/m^2)	Trail Length (/km)
Constraining weight	$422,390	$1,118,861	$79	$2,311,012

The DEA for Imja Lake highlights that in the high season lowering Imja Lake by 10 and 20 m is an efficient project whereas in the off season all three projects proposed can be efficient. In addition the DEA methodology allowed for the calculation of the range of damage category weights under which a project is efficient. Although the initial DEA conducted in MATLAB provided damage category weights, the combination reported is only one of a range of efficient weights. The valuable outcome from the MATLAB analysis was the designation of each project as efficient or inefficient. The MATLAB results will be more meaningful if monetary weights or constraints for the unvalued tangible damage categories can be estimated for Dingboche.

Within the DEA market constraints the maximum weight for each damage category that retains a project's efficiency was calculated as shown in Table 3.13. The maximum weight bounds the range of values that can result in the projects identified in Tables 3.11 and 3.12 being efficient. Although a unique valuation for the damage categories for each project could not be calculated with the information available, the results in Table 3.13 provide guidance on how the damages should be valued to justify costly mitigation works.

The full DEA methodology is ill-suited for the case of GLOF mitigation works at Imja Lake because estimates and constraints for the value of tangible damages from a

GLOF are not available. Therefore the methodology does not provide unique weights for the GLOF damage categories. Nonetheless, the methodology provides a useful framework to compare the proposed projects and to begin to consider the value of intangible and tangible consequences needed to justify mitigation works (Table 3.13). Despite the lack of data on the local valuation of damage categories, the methodology provided results for project efficiency (see Tables 3.10 and 3.11) and how the damage categories must be valued (see Table 3.13) to comply with DEA constraints and definition of efficiency. Decision makers for an Imja Lake project may wish to input estimated values for tangible damage categories, and calculate how intangible or non-valued consequences must be valued to comply with DEA constraints. At present the only guidance the DEA methodology provides for the valuation of tangible and non-valued consequences is the range presented in Table 3.13. The inclusion of more valuation data into the DEA framework used here will narrow the range of weights necessary for efficiency and provide greater information for decision makers.

Decision Analysis

Decision Analysis (DA) allows for the inclusion of uncertainty in the comparison of various decisions. The first step in conducting a DA is to construct a decision tree of the decision options and consequences. Figure 3.5 shows the decision tree for Imja Lake GLOF mitigation projects.

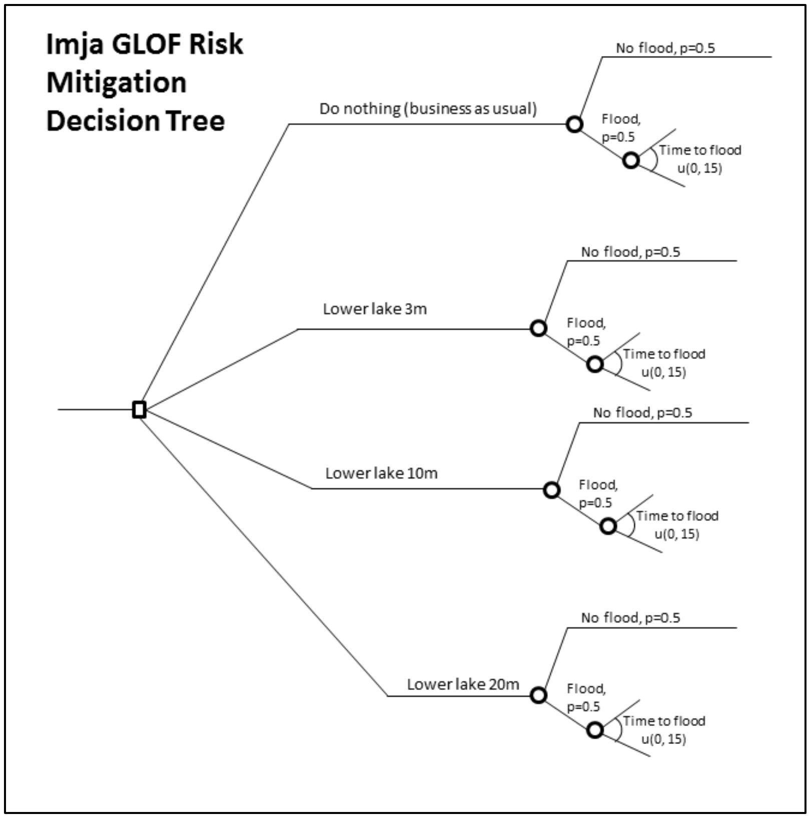

Figure 3.5. The decision tree for Imja GLOF risk mitigation shows the decisions under consideration (lake lowering amounts), probability of a flood, and time to flood distribution.

In this tree the maximum entropy probability distribution is used to reflect extreme uncertainty in GLOF prediction, meaning that equal probability is assigned to a GLOF occurrence and no GLOF. This decision stems from Laplace's "Principle of Insufficient Reason" which finds that in the absence of information suggesting otherwise, two events should be assigned equal probability. Laplace's reasoning is strengthened by information theory which shows that assigning two events equal probability has the greatest entropy and therefore is a product only of the (minimally) available information. (Jaynes 1957) A uniform distribution over 15 years (estimated project lifetime) is used to reflect uncertainty in the timing of a GLOF. The 15 year timeframe is used as the estimated project lifetime as recommended by an engineer that participated in the design of a project to lower Imja Lake by 3m (R. Parajuli, Personal Communication, 2016). Using the uniform distribution over 15 years for the time to a GLOF gives an expected value of flood occurrence in 7.5 years. The uniform distribution assigns equal probability to a GLOF occurring any time over the project lifetime and has the highest level of entropy while reflecting the known information. However, the assumption of a GLOF being equally likely over 15 years makes assumptions that diverge from the maximum entropy ideal. In particular, this work assumes a lifetime over which a GLOF may occur and applies equal probability to a GLOF event rather than to the consequences of a flood. At present insufficient information is available to refine the probability of a flood and its timing. These probability distributions can be updated as more is learned about Imja Lake and its risk for a GLOF.

With each year that it takes for a GLOF to occur the monetary damages need to be discounted to present value. A 6% annual discount rate is used here. The 6% discount rate is in keeping with recommendations from the US Office of Management and Budget (OMB) as applied to Nepal. In conducting cost benefit analyses, the OMB recommends that government agencies discount future costs and benefits at the same rate a typical saver would use to discount future benefits. If the policy primarily affects consumption by the individual, the recommended discount rate is 3% (corresponds to the real return rate of long term government bonds). When private capital is affected by a policy the recommended discount rate is 7% (corresponds to average return rate of capital in the US economy before taxes). (OMB 2003) The Nepal Rastra Bank (the central bank of Nepal) reports that in 2015 the rate of return for savings deposits was 2.8%. The weighted average lending rate over the same time period was 9.6%. (Nepal Rastra Bank 2016) These two values average to 6%. Because it is not known how the costs from an Imja GLOF would be distributed between individuals and damage to capital, the average discount rate is used in this analysis.

Unlike DEA, DA requires all costs and benefits to be valued in the same units, which means that a value must be assigned to fatalities (intangibles) and other damages. The estimated values of the damages quantified here are given in Table 3.14. The value for structure damage was estimated as described in the previous section.

Table 3.14. Estimates for the value of damage categories.

Fatalities	Structures	Ag. Land (/m^2)	Trail length (/km)
$330,436	$3,850	$300	$1,000

Estimating the value of a human life is a controversial and difficult task. Nonetheless researchers have been able to estimate the value of a percent reduction in the risk of death that employees and consumers are willing to pay (OMB 2003; US DOT 2013; Cropper & Sahin 2009). Extrapolating from the willingness to pay information researchers can estimate the value of a statistical life (Cropper & Sahin 2009). The Department of Transportation reports that the value of a statistical life (VSL) used for economic analyses by the US government in 2012 was $9.1 million, which corresponds to the range of VSL in the literature of $1 to $10 million that OMB reports. (US DOT 2013; OMB 2003) Because income in Nepal is much lower than in the US, the VSL in Nepal can be estimated using the ratio of real income in Nepal to that in the US (Cropper & Sahin 2009). TheWorld Bank's estimate of the Gross National Income per capita for the US (The World Bank 2014) and income per capita in Solu Khumbu adjusted to ensure purchasing power parity is used to adjust VSL for a Dingboche consumer (Sharma et al. 2014). Purchasing power parity adjustments ensure that the income in a given country would allow an individual to consume the same kinds and quantity of goods in another country. This adjustment ensures that the VSL conversion reflects the goods (utility) that a Nepalese consumer would be willing to trade for a decrease in the risk of death. The adjusted VSL for Nepal is $330,436.

The cost estimates for agricultural land and trail damage is a rough estimate given the researchers' experience in the region. Cost to repair or replace these damaged resources will vary with the amount of damage and timing of a GLOF. Therefore it is difficult to find estimates for these damage categories in the literature. Given the high uncertainty in these cost estimates a sensitivity analysis is conducted later in the chapter.

The cost estimates in Table 3.14 are combined with the probabilities in each branch of the decision tree (Figure 3.5) to solve the decision tree. This analysis gives the expected value of each decision. An example of how the decision tree is solved is given for the '3 m lowering' branch in Equation 3.2.

$$
\begin{aligned}
EV &= -\left(\frac{P_{GLOF}\,(\sum Value * Damages_{\Pr oject})}{(1+r)^{t}} + \frac{P_{NoGLOF}\,(\sum Value * Damages_{\Pr oject})}{(1+r)^{t}} + C_{\Pr oject} \right) \\
EV &= -\left(\begin{array}{l} \dfrac{0.5(3 * \$330436 + 14 * \$3850 + 86262 * \$300 + 7.85 * \$1000}{(1+0.06)^{7.5}} + \\ 0.5(0) + \$2260822 \end{array} \right) \\
EV &= -\$10959216
\end{aligned}
\tag{3.2}
$$

In Equation 3.2 the cost of a GLOF occurrence (damages in Table 3.7 times the value of each damage category as given in Table 3.14) is multiplied by the probability of a GLOF (0.5 as shown in Figure 3.5) and discounted to calculate its present value; the same procedure is followed for consequences of no GLOF (zero since there are no damages). The present value of the GLOF and no GLOF consequences are summed to give the expected value of each decision. Because a GLOF occurrence will only result in damages, the expected value of any branch's consequences is negative (they are costs). Likewise the cost of any mitigation works has a negative value. Therefore all decisions presented have a negative expected value. The expected values for the projects analyzed are summarized in Table 3.15. The lowest expected cost project is the most favorable decision, from an economic point of view.

Table 3.15. Expected costs for the proposed GLOF risk mitigation projects. Lowering the lake 10 m (highlighted in pink) is the lowest cost option for both seasons with the damage cost estimates used.

Project	Cost high season	Cost off season
BAU	-$10,168,818	-$9,315,023
Lower 3 m	-$11,172,665	-$10,639,043
Lower 10 m	-$8,190,538	-$8,190,538
Lower 20 m	-$8,806,972	-$8,806,972

The results from the decision analysis indicate that lowering the lake 10 m has the lowest expected cost of any of the projects proposed. This result holds in the high and off season.

Given that many of the values in Table 3.13 as well as the probabilities in the decision tree are uncertain, a sensitivity analysis is conducted to determine at what value for each of the variables does a project other than 10 m lowering have the lowest expected cost. For this analysis all other variables (other than the one analyzed) remained constant. In addition the high season fatality estimates are used in this analysis.

The sensitivity analysis showed that relatively small deviations in the decision tree variables results in a change in the lowest cost project from 10 m lowering to BAU or 20 m lowering. Table 3.16 contains the value at which the lowest cost decision changes from 10 m lowering for the values in the decision tree.

Table 3.16. Value of decision tree variables that change the lowest expected cost decision.

	Value	Lowest cost project	Value	Lowest cost project
Probability of flood	<0.34	BAU	>0.6	20 m lower
Discount rate	>0.11	BAU	<0.03	20 m lower
Time to flood (years)	>14	BAU	<4	20 m lower

The value of damages (except for project costs) that changes the lowest expected cost decision was also evaluated. Table 3.17 contains the value of damages that changes the lowest cost decision. Table entries with dashes indicate that even when the damage category is valued at zero, the lowest cost decision does not change.

Table 3.17. Sensitivity analysis for the estimated value of GLOF damages.

	Value	Lowest cost project	Value	Lowest cost project
Fatalities	--	--	--	--
Structures	--	--	$640,044	Lower 20m
Ag. Land (/m^2)	$185	BAU	$365	Lower 20m
Trail length (/km)	--	--	$680,211	Lower 20m

Table 3.17 shows that valuing fatalities at zero does not change the lowest cost decision when all other variables are held constant. Although the sensitivity analysis showed the lowest cost decision to hold over a wide range of values for the damage

categories, Table 3.16 shows that small changes in the decision tree variables may cause a change in the lowest cost decision.

In this analysis the maximum fatality rate was used for each flood severity category identified by Graham to estimate the worst case scenario and provide conservative recommendations. If the expected fatality rate is used, then fatalities in the high season decrease (in the low season fatalities are the same. Table 3.18 shows the fatalities and expected cost of each decision in the high season using the expected fatality rate. Using the expected fatality rate does not change the lowest cost decision, although fatalities for the BAU and 3 m lowering decision decrease.

Table 3.18. Fatalities and expected value of each decision using the expected fatality rate.

	Fatalities	Expected value
BAU	8	-$9,955,369
Lower 3 m	4	-$11,065,941
Lower 10 m	0	-$8,190,538
Lower 20 m	0	-$8,806,972

The decision tree and sensitivity analysis shows that damage to Dingboche from an Imja Lake GLOF justifies the cost of lowering the lake 10 m. This result holds under a range of values for GLOF damages, but changes with relatively small changes in decision tree variables. If more than one variable in Tables 15 and 16 change, than the thresholds presented will be different. Therefore the sensitivity analysis results should be used with caution. Given the sensitivity of the lowest expected cost decision to the decision tree variables, decision makers should carefully evaluate the variables used in this analysis to determine if they are reasonable for the community of Dingboche and rerun the analysis with amended values if necessary.

As more information is learned about the probability of a flood and likely time to occurrence, the decision tree variables in Figure 3.5 can be updated. New or updated probability distributions can then be used to solve the decision tree and obtain a better estimate of the expected cost of each decision.

DEA with expected damage values

To combine the DEA and decision analysis methodologies presented here the expected damage values are used in the DEA methodology. To do this the relative damage values for net benefits are adjusted using the likelihood of a GLOF (50%) and the time to a flood (7.5 years) with the discount rate (6%). Non-monetary damages are combined using the probability of a GLOF but not discounted. In addition the high and off season fatalities are combined by assuming that the high season lasts seven months and the off season lasts five months. Therefore the expected fatalities are estimated by multiplying each category by the percentage of the year the season lasts (7/12 for the high season and 5/12 for the off season) and add the two values. This method assigns equal probability to a GLOF occurring in each month of the year. Table 3.19 contains the expected relative damage values.

Table 3.19. Expected relative damage values were calculated by multiplying relative damage by the probability of a flood and applying the discount rate over 25 years.

	Net benefits	# of people unhurt	Area ag unhurt (m^2)	Trail length undamaged (km)	Building damage
3m decrease	-$2,253,361	2	2,386	0.06	$7,461
10m decrease	-$4,265,601	3	17,255	0.26	$19,896
20m decrease	-$7,745,194	3	26,796	1.67	$23,626

Because the cost of lake lowering would be paid in the present and is not uncertain, the cost of lake lowering remains unchanged from the values given in Table 3.9 (this value is subtracted from building damage costs to give the net benefits category in Table 3.19). The damages, on the other hand, are uncertain and would occur at some time in the future. However, only monetary building damage costs are discounted, since the damage quantity does not change with the timing of the GLOF event. The expected value of all damages (given in Table 3.19) is lower than the values in Table 3.8 due to the inclusion of uncertainty. Table 3.20 summarizes the result of the DEA with expected damage values.

Table 3.20. DEA with expected damage values finds that 3 m, 10 m and 20 m lake lowering are efficient decisions.

	Costs	Fatalities	Ag. Land (/m^2)	Trail length (/km)	Project value
Lower 3m	-\$1	\$1,081,306	\$18	\$810,572	\$9.5e-08
Lower 10m	-\$1	\$221,355	\$198	\$706,053	-\$9.3e-08
Lower 20m	-\$1	\$223,928	\$155	\$1,756,490	-\$4.5e-08

The expected damage DEA shows that all three projects are efficient when uncertainty in the occurrence and timing of a GLOF is included as specified in the decision tree in Figure 3.5. As with the previous DEA results, projects are efficient under a range of weights for the three damage categories. Table 3.21 contains the constraining weights for each category under which lowering the lake 10 m and 20 m is an efficient decision. These results were calculated using the method illustrated in Table 3.12.

Table 3.21. Constraining weights for expected damages under which lowering the lake is efficient.

Fatalities	Ag. Land (/m^2)	Trail length (/km)
$1,126,680	$247	$4,651,768

The maximum weights for the expected damages are higher than those for raw damages (see Table 3.13). This result is expected because lower benefits are justified with the same cost when assessing expected damages.

This analysis shows that if uncertainty in the occurrence and timing of a GLOF is taken into account, damages must be valued higher than when uncertainty is not considered. Although the DEA methodology does not explicitly account for uncertainty, it can be included by using expected damage values. The analysis shows that lowering the lake 3, 10 and 20 m are efficient decisions even when uncertainty in the timing and occurrence of a GLOF is considered.

CONCLUSIONS

This analysis shows that the damage from a GLOF from Imja Lake in Dingboche is sufficient to justify the cost of lowering the lake 10 m under the price estimates used here. In addition this decision is economically efficient as demonstrated by the DEA. Using expected values in the DEA shows that lowering the lake 3 m, 10 m and 20 m are efficient decisions when uncertainty in the timing and occurrence of a GLOF is considered. Therefore if the decision tree values shown in Figure 3.5 are valid, then lowering Imja Lake 10 m is the best decision from an economic standpoint. Although, if costs for the damages in Dingboche are significantly less than those used here or if the decision tree variables differ from the values shown in Figure 3.5, the lowest cost decision will change and the efficiency of the proposed projects will need to be reassessed.

In this analysis the damages in Dingboche from an Imja GLOF including fatalities and damages to infrastructure were successfully estimated. In addition the cost for the lake lowering works proposed was estimated. This information allowed for the comparison of the proposed projects based on their benefits (decreased damage) and costs.

Although the DEA methodology was successfully utilized to identify efficient projects for Imja Lake, the methodology is not well suited to the problem analyzed here. Because of the lack of benefits other than deferred damages from any of the projects, the BAU decision could not be assessed. In addition, the lack of validated cost estimates for tangible damages (too many degrees of freedom) and insufficient constraints on the value weight (price) of intangibles led to projects being efficient under a range of weights, rather than for a unique combination of weights. Nonetheless, the framework of the DEA methodology proved useful for framing the decision (a competitive marketplace of projects) and for calculating a range of prices under which decisions are efficient.

Likewise, the DA methodology allowed for the comparison of proposed projects taking into account uncertainty in the timing and likelihood of a GLOF. However, the DA methodology required that the cost of unvalued infrastructure and VSL be estimated for Dingboche. The DA found that the lowest cost decision was lowering the lake 10 m and that the decision is sensitive to small changes in the decision tree variables (Figure 3.5).

The DA and DEA methodologies were combined by using expected values in the DEA. This approach showed that lowering the lake 3, 10 or 20 m is an efficient decision when uncertainty in the timing and occurrence of a GLOF is considered. This result is meaningful because it does not require that the value of intangibles or unvalued infrastructure be estimated. Because DEA as applied here cannot compare the BAU decision to the proposed projects, this result must be considered in the context of the DA result.

Future work should include modelling the damage from an Imja GLOF downstream of Dingboche and using new information to update the decision tree variables. Significant damages downstream may change the lowest cost decision arrived at here. Given the damages estimated in Dingboche and the sensitivity analysis, the addition of greater benefits (decreased damage downstream of Dingboche) may make refinement of the uncertain variables in this analysis unnecessary. In addition, any new information on the likelihood and timing of a GLOF should be used to update the probability distributions in the decision tree (Figure 3.5). Updated damage and probability distributions can be used in the decision making methodology to refine the estimate of the best decision from an economic standpoint for Imja Lake. weUltimately, though, the decision of what project to pursue is made considering social values and preferences. Although economic analyses such as those presented here can inform the process, the decision will likely not be a purely economic one.

Chapter 4: Lake Palcacocha Analysis

INTRODUCTION

Lake Palcacocha (coordinates 9°23’34” S, 77°22’46.4” W) is located in the Peruvian Andes and contributes to the Quillcay sub-basin, which is part of the Rio Santa basin (Figure 4.1). Lake Palcacocha drains to the Paria River in the Cojup valley, which leads to the major city of Huaraz (Pop. 100,000 according to the 2007 census).

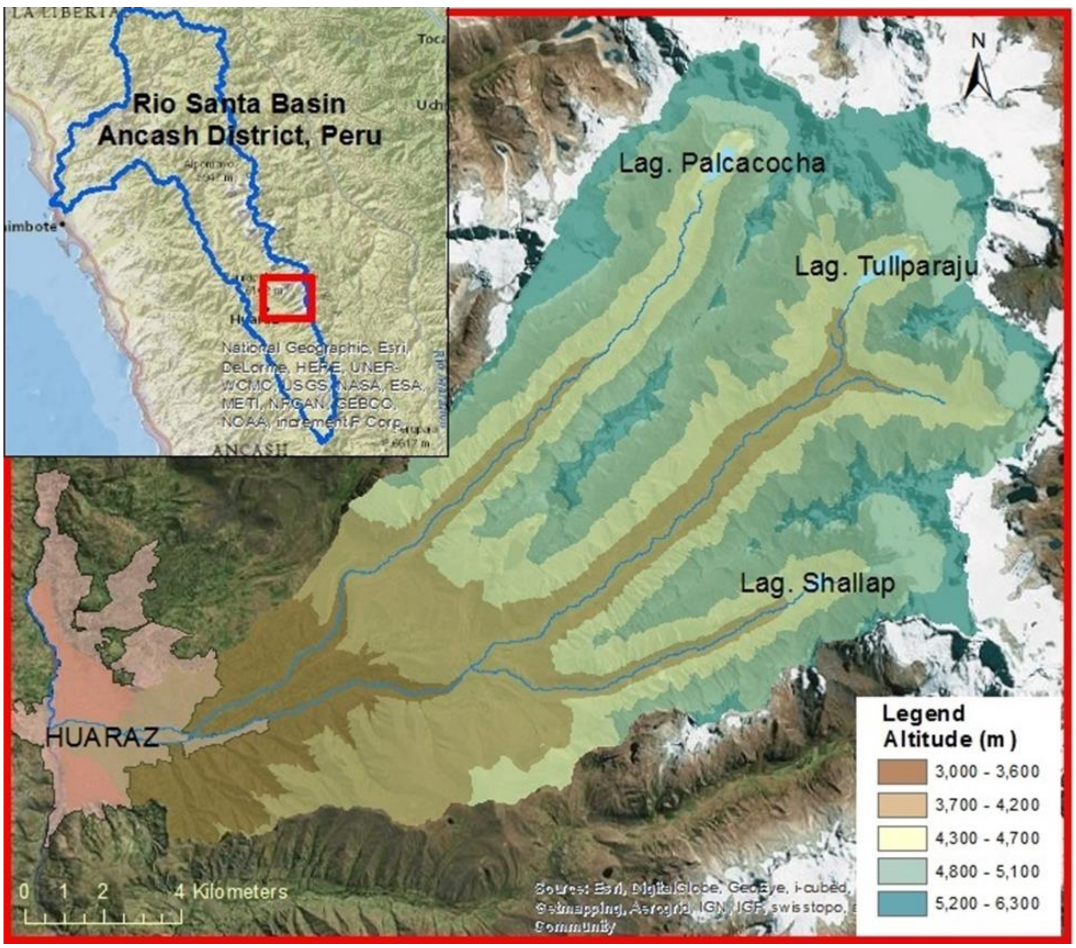

Figure 4.1. Map of the Quillcay sub-basin and Lake Palcacocha, which is located in the Rio Santa basin in Peru.

Lake Palcacocha was formed when the Cojup glacier retreated at the end of the Little Ice Age. In 1941 Lake Palcacocha experienced a catastrophic avalanche triggered GLOF event that destroyed approximately one third of the Huaraz city center and resulted in 1800 to 5000 fatalities (Carey 2010; Somos-Valenzuela et al. 2016; Portocarrero 2014). At the time of the 1941 GLOF Lake Palcacocha contained between 10 and 12 million m^3 of water, which decreased to 500,000 m^3 after the flood event (Portocarrero 2014). After the 1941 flood the lake continued to grow reaching a volume of over 17.3 million m^3 of water at present (Somos-Valenzuela et al. 2016).

In an effort to decrease the risk of a GLOF from Lake Palcacocha, in 1974 the Peruvian government constructed a drainage system to lower the lake 1m and maintain 8m of freeboard between the water surface and dam crest. Despite the lake lowering project, a landslide from the lateral moraine (South) into the lake in 2003 produced a wave in the lake that damaged the dam, but resulted in no serious flooding in Huaraz. In 2011 further lake lowering by 3 to 5m was undertaken using siphons to provide a total freeboard of 12m. (Portocarrero 2014) The existence of steep slopes in close proximity to the lake's surface creates the risk of another avalanche induced wave in the lake, which may trigger a GLOF (Somos-Valenzuela et al. 2016). As the lake continues to grow, the size of an avalanche induced wave and its potential to overtop the terminal moraine and cause a GLOF downstream increases.

Given Lake Palcacocha's physical characteristics it is considered to pose a high risk to the population living downstream (Emmer & Vilimek 2013). Stakeholders in Huaraz have expressed concern about a potential GLOF from Lake Palcacocha and have proposed works to mitigate the risk posed by the lake (Portocarrero 2014). At present the proposed risk mitigation projects consist of further lowering of Lake Palcacocha and reinforcement of the moraine to decrease hydrostatic pressure on the terminal moraine and the amount of water that could contribute to a future GLOF (Portocarrero 2014). Additionally, an Emergency Warning System (EWS) for a GLOF from Lake Palcacocha has been priced for Huaraz (Personal communication, Cesar Portocarrero, 2016). Although potential GLOF scenarios have been identified and the hydrodynamics of the flood modeled, at present a rigorous analysis of the costs and benefits of GLOF mitigation projects has not been conducted in part because of a lack of information on the consequences, uncertainty, and costs of the proposed projects.

In this chapter the decision making methodology is applied to projects proposed to mitigate the likelihood and damage from a potential GLOF from Lake Palcacocha. Lake Palcacocha is considered a high data case since detailed demographic and geographic information for the region is available in contrast to the low data case of Nepal.

LAKE PALCACOCHA ANALYSIS

The objectives of this analysis are to identify likely GLOF scenarios and mitigation projects, estimate damage from a potential GLOF to people and structures with and without mitigation measures, identify economically efficient mitigation projects taking into account intangible damages from a GLOF, and to identify the least expected cost project taking into account uncertainty in the timing and occurrence of a GLOF. The analysis consists of: (1) identifying likely GLOF and lake lowering scenarios; (2) estimating the consequences of each flood and lake lowering scenario using available demographic data and a detailed flood consequence model (3) conducting an economic analysis to determine the efficiency and expected cost of proposed projects. The analysis conducted here will help to identify the efficient and lowest expected cost projects taking into account the limited data and uncertainty surrounding a GLOF from Lake Palcacocha.

Scenario Analysis

The analysis at Lake Palcacocha begins by identifying the potential GLOF scenarios and mitigation projects for the lake. These scenarios were identified and studied by Somos-Valenzuela et al. (2016) where an avalanche induced wave was identified as the most likely trigger for a GLOF from Lake Palcacocha. Three potential avalanche events from the Palcaraju glacier were identified and analyzed: large (3 million m^3 volume), medium (1 million m^3), and small (500,000 m^3). The process chain resulting from each identified avalanche event was modeled starting with avalanche flow down the glacier slope into the lake, wave propagation across the lake, terminal moraine overtopping and dynamics, and debris flow down the Cojup valley to Huaraz. Flood levels in Huaraz were modelled for three scenarios: 0 m lake lowering, 15 m lake lowering, and 30 m lake lowering. The modeling showed that the terminal moraine withstood wave overtopping without failing for all scenarios modeled. In addition, the researchers concluded that when the lake is lowered by 15 and 30 m a small avalanche event does not cause flooding in Huaraz. (Somos-Valenzuela et al. 2016)

Based on the work of Somos-Valenzuela et al. (2016) and personal communication with Cesar Portocarrero the following scenarios are considered in this work: 0 m lowering with and without EWS and a small, medium, and large avalanche; 15 m lowering with and without EWS and a medium and large avalanche; 30 m lowering with and without EWS and a medium and large avalanche. All lowering scenarios also include moraine reinforcement works. Figure 4.2 shows the extent of the maximum flood scenario: 0 m lowering and a large avalanche into the lake.

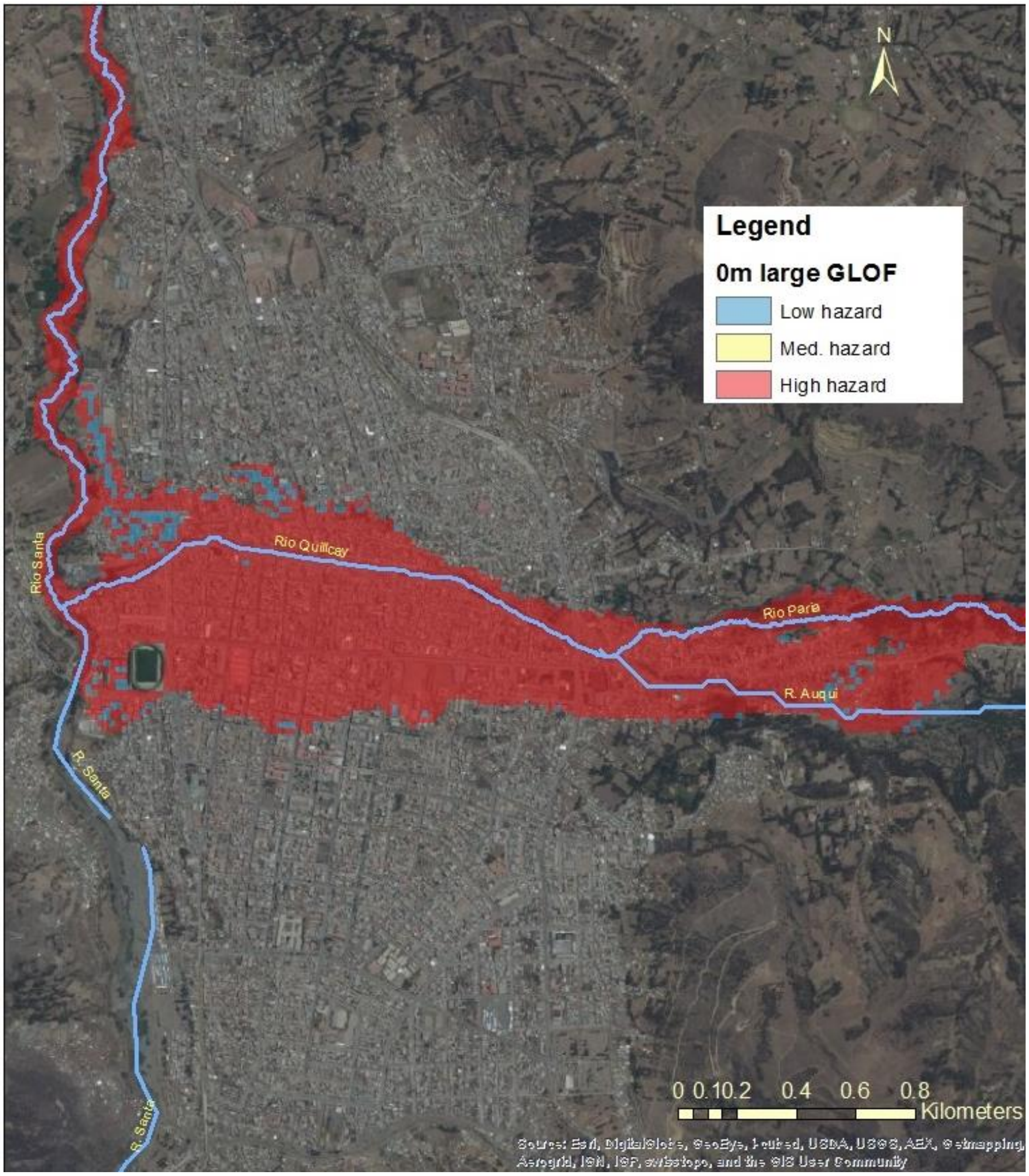

Figure 4.2. Flood extent and hazard levels from a large GLOF with no lake lowering and no moraine breach covers the center of Huaraz City.

HEC-FIA consequence estimation

The Hydrologic Engineering Centers Flood Impact Analysis (HEC-FIA) software is a dynamic flood consequence estimation model developed by the US Army Corps of

Engineers (USACE 2012). As mentioned in the methods section (Chapter 2), HEC-FIA uses flood characteristics as well as warning time and empirical evacuation curves to estimate fatalities and structural damage. Although the model can accept and use detailed demographic and economic data for the region modelled, it also contains default data and simplifications for use in regions with less data availability. Additionally, the default damage functions and thresholds can be altered in locations where more tailored information is available, as is the case here (USACE 2015). Therefore, HEC-FIA is used with the data sets available for Huaraz and structure damage thresholds are incorporated that reflect the vulnerability of structures in South America to a debris flow event (Garcia-Martinez & Lopez 2007).

HEC-FIA was adapted to reflect conditions of a Peruvian city and to the limits on data availability for Huaraz. Details of the adaptation and results from the HEC-FIA model for the scenarios assessed in this work are presented.

HEC-FIA model configuration for Huaraz

The first step in configuring the HEC-FIA model is to input map layers to define the study area. Map layers include a polygon outlining the impact area (Huaraz city outline), the stream alignment, a building inventory shapefile, and a flood hazard area outline. The flood hazard outline is used later in the structure inventory module to define the safe zone outside the reach of flood waters.

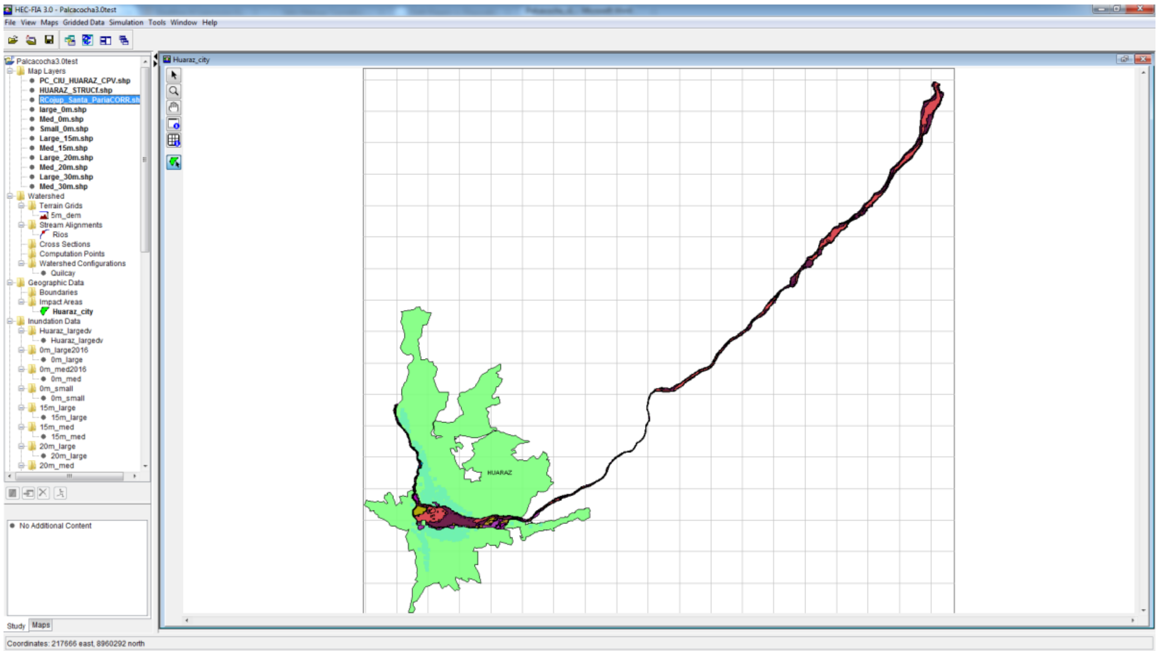

Figure 4.3. HEC-FIA main page with initial map layers visible.

In addition to shape files, HEC-FIA requires the inclusion of a DEM to assign structure elevations. A 5m DEM recently developed by the Peruvian Ministry of Environment (Horizons South America S.A.C. 2013) was used here as the HEC-FIA terrain grid. This is the same DEM used in the FLO-2D modelling of the GLOF (Somos-Valenzuela et al. 2016).

HEC-FIA allows the user to provide inundation data either as hydrographs or grids depending on the modelling software used and its outputs. The easiest inundation data to produce from FLO-2D results are grids. HEC-FIA requires that the user input grids for the instantaneous maximum depth times velocity (d*v), maximum depth, and time of arrival for flood waters. Arrival time is defined as the time at which flood waters reach the non-evacuation depth in each grid cell. The recommended non-evacuation depth is 2 ft; this value is derived from adult toppling in water experiments (McClelland

& Bowles 2002; Needham et al. 2010). The FLO-2D results were used along with a program provided by HEC-FIA developer William Lehman to generate the three input grids.

To estimate the time taken to evacuate and therefore whether individuals can evacuate the flood plain before flood waters arrive, HEC-FIA requires the input of a polygon delimiting the flood extent. Individuals that can reach the limits of the flood polygon before waters reach the non-evacuation depth are considered safe. The flood polygon was derived from the 2 ft (non-evacuation depth) grid using ArcGIS.

HEC-FIA's use of a building inventory with the optional input of extensive demographic data makes the model highly customizable but also easy to use with limited data. Because a building inventory for the cityis not available, the Huaraz city block census shapefile was used to create the building inventory. The Huaraz census was conducted in 2007 and provides demographic data for the population at the city block resolution. Information on the population age, structure classification, structure occupancy types (residential for all buildings detailed in the census), foundation height, and structure value in the building inventory was included in the census and used in HEC-FIA.

The census includes counts of population over 65 and total population. Using these two values a count was created of the two age categories used by FIA (younger and older than 65). FIA assumes that populations younger than 65 can reach and remain safe at higher elevations on buildings when evacuating vertically than older individuals (USACE 2015).

HEC-FIA is loaded with default depth damage curves for several structure classifications (for example, single story-single family with and without basement, multi-family buildings by number of units, and mobile homes) and can be customized by the inclusion of structure and foundation height. The default depth damage curves are based on curves in the HAZUS model (USACE 2015) and depend on the structure classification. Because only information on home categories for each city block was available, the structure classification was assigned to each block that represents the majority of inhabitants. Therefore if over half of the population in a city block resides in multi-family structures, then the entire block was designated as a multi-family dwelling. The number of stories for each dwelling is important in HEC-FIA because it determines how high residents can climb to escape rising waters (USACE 2015). This information was not provided in the Huaraz census, therefore all buildings were designated as single story structures. Foundation height is also instrumental in predicting when a building will be inundated (USACE 2015). The default foundation height in HEC-FIA is three feet. Foundation height in the areas of the city near the river ranged from about 0.5 to 1 ft, although some foundations were up to 3 ft high and others were below street level (R. Chisolm, Personal Communication, 2016). The foundation height was designated as 1 ft to provide a lower bound for estimates of building damage.

In order to estimate monetary structure damage, HEC-FIA requires the user to input the value of every entry in the structure inventory. The structures in each city block were designated a value of $100. This was done so that building damage could be reported as a percentage and later adjusted with estimates for building value.

Although HEC-FIA allows the user to enter custom depth damage curves for their study area, sufficient information was not available on the relationship between water depth and building damage for Huaraz city. Therefore the built-in depth damage curves in HEC-FIA were used, which reflect building characteristics in the United States. The newest version of HEC-FIA (3.0) also uses depth times velocity (d*v) to estimate building damage. García-Martínez and López (2007) studied a 1999 debris flow event in Venezuela and determined the flood characteristics (depth and d*v) that result in low, medium and high event intensities. This information was used to modify the d*v thresholds in FIA to better reflect the vulnerability of South American construction to flood waters. Partial building failure was specified to occur at 2.15 ft^2/s (0.2 m^2/s) and total failure to occur at 10.8 ft^2/s (1 m^2/s) in accordance with the findings of Garcia-Martinez and Lopez (2007).

Users of HEC-FIA must define a warning issuance scenario for each simulation. Because Huaraz does not have an early warning system (EWS) for GLOFs at present, it is assumed that inhabitants will become aware and be warned of a flood when flood waters reach the city limits. The time at which inhabitants become aware of a GLOF is identified by defining a point where the Paria River enters the city and finding the time at which the flood waters reach 2 feet at that point. Time is given in hours after the GLOF event begins (see Table 4.1). For the EWS that has been designed but not yet installed it is estimated that it would take 5 minutes for detection, verification and warning issuance for a GLOF (C. Portocarrero, Personal Communication, 2016). To allow for variability in the implementation and design of the early warning system, the EWS scenario is modelled with a warning issuance 10 minutes after the GLOF event.

Table 4.1. Warning initiation time given in hours after GLOF event begins for various avalanche sizes and lake lowering scenarios.

Lake lowering scenarios	GLOF trigger		
	Large avalanche	Medium avalanche	Small avalanche
0 m lower	1.4	3.0	8.7
0 m lower EWS	0.167	0.167	0.167
15 m lower	1.6	6.0	--
15m lower EWS	0.167	0.167	--
30 m lower	1.9	15.8	--
30m lower EWS	0.167	0.167	--

Warning initiation begins a cascade of flood evacuation events. A flood warning is diffused throughout the population, and after individuals receive the warning there is a delay until they mobilize (although some never mobilize at all) and then evacuate the flood plain (Aboelata & Bowles 2005; Fields et al. 2012). The warning diffusion and mobilization versus time curves are built into HEC-FIA (USACE 2015). The default mobilization curve in HEC-FIA is used here and sirens are used as the warning system. Although Huaraz does not presently have an EWS, the warning system must be specified for all simulations to define how the flood warning is disseminated throughout the population. Figure 4.4 shows the warning and mobilization curves used in the HEC-FIA model.

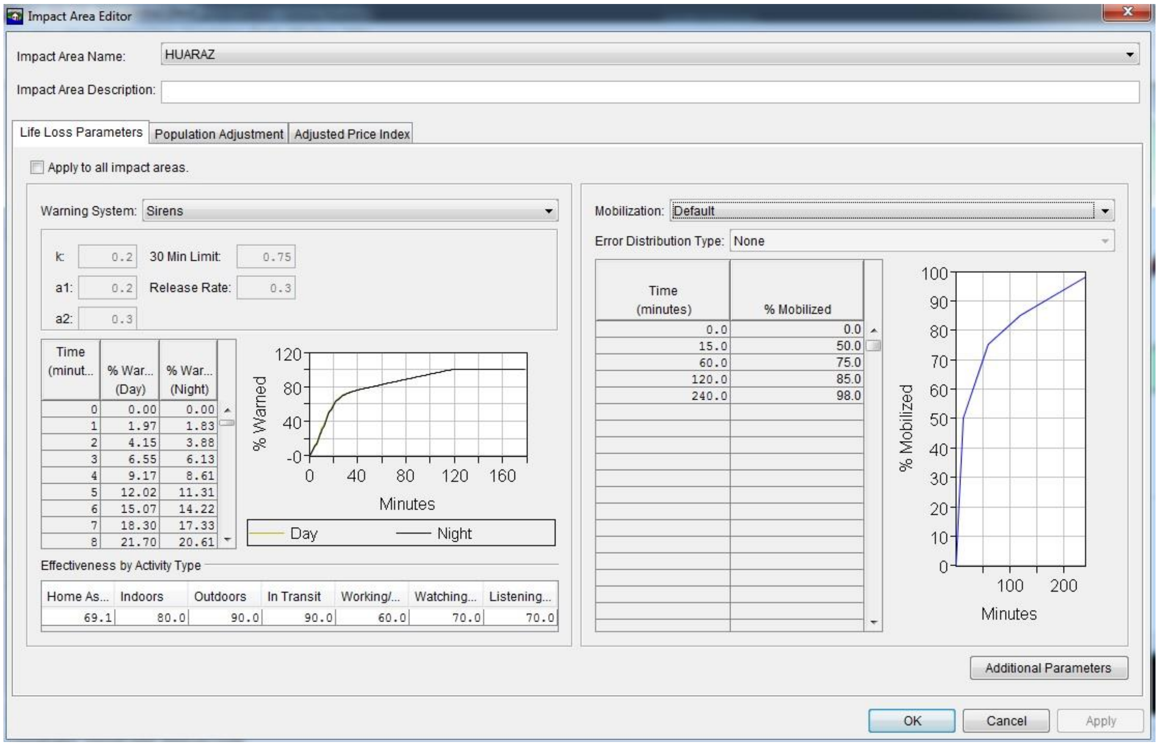

Figure 4.4. Built-in warning and mobilization curves are used in HEC-FIA.

HEC-FIA has two options for modelling evacuation: the user can either define the amount of time it takes for individuals to evacuate the flood plain or let HEC-FIA compute time for evacuation based on an evacuation polygon and travel speed to the safe zone. The latter method is used here. An evacuation speed of 3 miles per hour is used to reflect moderate walking speed (USACE 2012).

Although HEC-FIA allows for the inclusion and calculation of uncertainty of foundation height, structure value and depth-damage functions, these were not considered in this work because information is not available on the distribution or parameters for the variables used in the model. Instead best estimates were used for all variables to calculate the expected value of the GLOF consequences.

Results

HEC-FIA provides estimates for the number of fatalities, buildings inundated, and structure damage. The results from the HEC-FIA model are summarized in Table 4.2 below.

Table 4.2. HEC-FIA results for each lake lowering scenario and GLOF trigger (avalanche) size. Structure damage given in dollars when all structures are valued at $100.

	Avalanche size	Total fatalities	City blocks inundated
0 m lowering	Large	6125	154
	Medium	288	116
	Small	5	65
0 m + EWS	Large	2307	154
	Medium	134	116
	Small	5	65
15 m lowering	Large	3135	131
	Medium	11	71
15 m + EWS	Large	1052	131
	Medium	11	71
30 m lowering	Large	2347	121
	Medium	4	61
30 m + EWS	Large	627	121
	Medium	4	61

The results in Table 4.2 show significant fatalities for a large flood in all lake lowering scenarios. This result is due to flood waters from a GLOF passing through the middle of Huaraz. The highest hazard flood region is also highly populated, leading to significant building damage and fatalities. Nonetheless, lowering the lake level can decrease fatalities by 49% (15 m lowering) and 62% (30 m lowering). Similar improvements in the number of fatalities from the large GLOF, however, can be attained by the implementation of the EWS. Fatalities decrease by 62%, 66%, and 73% for a large avalanche and 0 m, 15 m, and 30 m lowering, respectively, with the addition of the EWS.

Fatalities from a Lake Palcacocha GLOF were estimated by Somos-Valenzuela (2014) using a modified LIFESIM method. Somos-Valenzuela estimated fatalities to be 19,773±1,191 without the EWS and 7,344±1,446 with the EWS. However, this estimation was conducted for the case of a large avalanche into Lake Palcacocha and complete failure of the terminal moraine. Recent work has concluded that failure of the terminal moraine at Lake Palcacocha will not occur in the event of an avalanche induced GLOF (Somos-Valenzuela et al. 2016). Given that the results are for a scenario not considered here, they cannot be compared to the estimates in Table 4.2.

Although this analysis only considers lowering the lake up to 30 m, further lowering of the lake would eventually lead to zero fatalities and damage to structures. As lake lowering continues, however, costs will increase (although at some point the EWS will no longer be needed and the cost to avoid fatalities will decrease), making extreme options unfeasible. Additionally, design hurdles may be so great (for instance, the need to drill through bedrock at the base of the moraine to build a spillway at the new lake level) as to make lowering infeasible.

To better estimate the actual cost of damage to buildings in Huaraz, the cost of rebuilding or repairing damaged structures was calculated. Cost estimates per m^2 to construct a new home in Peru were available from the Instituto de Desarollo e Investigación Construir (Institute for development and construction research) (IDIC 2016), and used to estimate a range of potential rebuilding costs for Huaraz. Cost estimates were given for a home with finishes ranging from basic to luxurious. To provide a conservative estimate for the damage to buildings from a GLOF the home cost estimate was based on basic finish costs on the low end (\$227/m^2) and high quality finish costs (\$503/m^2) for the high estimate. The construction cost was combined with estimates for the size of a home in Huaraz to estimate the cost of rebuilding a home. Using real estate websites for Peru, it was found that homes for sale in Huaraz in the city center (flood plain area) range from 50 to 163 m^2 (538 to 1754 ft^2)[2]. Using the construction costs and home size in central Huaraz, home costs were estimated to be between $11,350 and $80,480.

The cost of structure damages were computed using the percent damage in each city block (obtained from HEC-FIA) as well as the number of homes in each city block (reported in the census) and the home construction cost estimate. Equation 4.1 shows the method to estimate the damages in each city block.

$$C_{damage} = \%damage * \#homes * construction\ costs \tag{4.1}$$

Using Equation 4.1 the damage to structures due to a GLOF was calculated as summarized in Table 4.3.

Table 4.3. Estimate in USD for structure damage due to a GLOF from Lake Palcacocha.

Lake lowering	Avalanche size	Structure damage low	Structure damage high
0 m	Large	$43,435,146	$307,987,713
	Medium	$20,261,249	$143,667,431
	Small	$2,087,310	$14,800,594
15 m	Large	$38,226,296	$271,053,067
	Medium	$3,387,775	$24,021,864
30 m	Large	$32,962,634	$234,763,967
	Medium	$1,394,027	$9,884,698

[2] Websites for real estate listings: http://urbania.pe, http://departamento.mercadolibre.com.pe, http://casas.cari.pe

Vulnerability Assessment

Vulnerability constitutes the human component of risk. In particular, vulnerability is a measure of the harm to individuals and society resulting from a damaging event (the hazard) (Schmidtlein et al. 2008; Fuchs et al. 2012), and is a crucial component of disaster planning and management. Nonetheless, vulnerability remains an abstract concept without a universally agreed upon definition or a means of direct measurement (Schmidtlein et al. 2008). For the purposes of this study the 'humans as cause' tradition is used for defining vulnerability. The 'humans as cause' school of thought contends that human actions and characteristics, not just their exposure to a hazard, contributes to making a hazard event a disaster (Anderson 2000). Therefore, vulnerability of a community is determined by the characteristics of its inhabitants. For this study the focus will be on social vulnerability, which refers to a community's ability to withstand a hazard event (Hegglin & Huggel 2008). Other aspects such as exposure, which some sources combine in a measure of physical vulnerability (Hegglin & Huggel 2008), will be considered a characteristic of the hazard and not addressed in the social vulnerability index.

In this study a literature sourced social vulnerability index is adapted to quantify vulnerability to a GLOF hazard. The adapted index, termed SoVI_GLOF, is applied to the city of Huaraz to determine the relative vulnerability of each block to a GLOF using census data from 2007.

Methodology

The application of the SoVI to the city of Huaraz is constrained by the data collected in the census and the availability of only the 2007 census (no interyear comparisons are possible). Of the thirteen indicators applicable at the city block scale, the data necessary to evaluate only eleven indicators was available. The eleven indicators evaluated are listed in Table 4.4 with a quantitative description to explain how they were evaluated. In keeping with the SoVI methodology all indicators are normalized either by an appropriate denominator (Socioeconomic status, Employment Loss, Rural/Urban, Family Structure, Residential Property, Renters, Occupation, Special Needs) or by the population in each block (all other indicators). A more detailed description of the indicators follows.

Table 4.4. List of indicators used in Huaraz social vulnerability assessment and quantitative description of each indicator.

Indicator	Quantitative Description
Socioeconomic status	$\text{SOCIOECO} = \dfrac{(\text{salary executive} * \text{\# of executive}) + (\text{salary employee} * \text{\# of employee}) + (\text{salary laborer} * \text{\# of laborer})}{\text{pop.}}$
Race and ethnicity	$\text{RACE} = \dfrac{\text{speakers of a native language}}{\text{pop.}}$
Age	$\text{AGE} = \dfrac{\text{pop.} \leq 14 \text{ years} + \text{pop.} \geq 65 \text{ years}}{\text{pop.}}$
Employment Loss	$\text{EMPLOSS} = \dfrac{\text{pop. looking for a job}}{\text{pop. with a job} + \text{pop. looking for a job}}$
Rural/Urban	$\text{RUUR} = \dfrac{\text{total pop. block}}{\text{block area in m}^2}$
Residential Property	$\text{RESIPROP} = \dfrac{\text{\# of low quality homes}}{\text{total homes}}$
Renters	$\text{RENTERS} = \dfrac{\text{\# of rented homes}}{\text{total homes}}$
Occupation	$\text{OCCUP} = \dfrac{\text{\# of workers in agriculture or aquaculture}}{\text{total workers}}$
Family Structure	$\text{FAMSTRUC} = \dfrac{\text{pop.} \leq 14 \text{ years} + \text{pop.} \geq 65 \text{ years}}{\text{total \# of family heads}}$
Social Dependence	$\text{SOCIDEP} = \dfrac{\text{\# of people living from pension or retirement}}{\text{pop.}}$
Special Needs Population	$\text{SPENEEDS} = \dfrac{\text{\# of households with people with disbailities}}{\text{total households}}$

Socioeconomic status: This indicator relies on the income of residents in each city block using the employment categories reported for residents of each block in the census. Average monthly salaries by industry reported by the Peruvian Ministry of Labor

(Ministerio de Trabajo y Promocion de Empleo 2007) were used. Salaries in each industry are also broken down by employee classification (laborer, executive, employee), which corresponds with employment information provided in the Huaraz census. Although the census provides information on the industries in which people in each block work, the categories are not the same as those given in the labor statistics from the Peruvian government. Therefore the average of the salary for each job category using all industries listed is used (salaries used are summarized in Table 4.5). The salaries for executive, employee and laborer have been multiplied by the number of people that hold each of those job categories in a city block and divided by the population of the block.

Table 4.5. Average salaries per month in Nuevos Soles (1USD = 3.31 NS) used for each employee classification to calculate the socioeconomic status of each city block in Huaraz (Ministerio de Trabajo y Promocion de Empleo 2007).

Executive	Employee	Laborer
2124	775	440

Race and ethnicity: Language and culture barriers may affect if an individual lives in a flood prone region or their ability to solicit aid in the aftermath (Cutter et al. 2003). An individual's native language gives some insight into the ethnic origin of a family. Therefore the language spoken by individuals in each household is used as an indicator of race and ethnicity. Individuals with native ancestry are considered vulnerable. From the Huaraz census the following language categories have been considered as native: Quechua, Aymará, Ashánika and other native language.

Age: Older and very young populations are considered more vulnerable (Cutter et al. 2003; Hegglin & Huggel 2008). Three age groups from the census have been considered as "extremes". The younger spectrum includes two age groups: less than 1 year old and 1 to 14 years old. The older spectrum includes one group: 65 or more years old.

Employment loss: Unemployment diminishes a community's ability to recover from a disaster by contributing to the population out of work after a hazard event (Cutter et al. 2003). For this indicator the economic definition of unemployment shown in Table 4.4 is used.

Rural/urban: The urban component of this indicator reflects the difficulty of evacuating a densely populated area (Cutter et al. 2003). Therefore, population density for each city block is used as a measure of the urban component of vulnerability. This indicator is also used in the Peruvian vulnerability assessment for Huaraz (INDECI 2003).

Residential property: The houses in each block have been categorized according to construction material in the city census. Low quality house construction is defined as having walls constructed from rush mat, adobe without structural support, or wood, which also corresponds to the lowest quality housing material categories defined by the Peruvian government (INDECI 2006). Construction materials are reported in the census for each home in the city.

Renters: Renters may lack the resources to own a home or be transient. Therefore home ownership status reflects socioeconomic class and populations that may be at greater risk if housing stock is constrained after a hazard event. (Cutter et al. 2003)

Occupation: Employment sectors that rely on resource extraction may experience disruption in the event of a hazard. In the case of a GLOF the agriculture sector would be damaged, for example irrigation water capture points along the river may be damaged or fields in the path of a GLOF may experience erosion. Some Huaraz residents also practice aquaculture along the banks of the rivers. These operations would also be affected by a flood. Therefore agriculture and aquaculture are considered as occupations vulnerable to a GLOF.

Family structure: The number of dependents per family head is used to define this indicator. Families with a large number of dependents per family head may find it harder to evacuate in the event of a flood and have more family responsibilities to balance, making recovery difficult (Cutter et al. 2003). Dependents are defined as anyone under 14 years and above 65 years of age.

Social dependence: People whose survival depends completely on social services are considered vulnerable because of their socioeconomic state (Cutter et al. 2003). This indicator quantifies the number of people that claim their primary income from a pension. Although the census contains sufficient information to quantify the social dependence indicator, there may be other types of social dependence in Huaraz that are not reflected in the census, such as those receiving government aid or other services. Therefore, the social dependence indicator used here is a lower bound.

Special needs population: The census provides information on the number of households with a disabled member, but it does not say how many people with a disability there are in each household. Therefore, the indicator has been defined per house, not per person as shown in Table 4.4.

In addition to the eleven indicators listed in Table 4.4 above an additional five more indicators were developed to include the local values reflected in the Peruvian study and conditions that contribute to vulnerability from a GLOF. The characteristics of a GLOF and the data available in the census were taken into account to develop the indicators described in Table 4.6.

Table 4.6. Peru and GLOF specific vulnerability categories and their quantitative description.

Category	Quantitative description
Sanitary services	$\text{SANITARY} = \dfrac{\#\text{black well} + \#\text{river or similar} + \#\text{nothing}}{\#homes}$
Communication and media	$\text{COMMUN} = \dfrac{(\#\text{ radio} + \#\text{ color TV} + \#\text{ land phone} + \#\text{ cell phone} + \#\text{ internet connection})}{pop.}$
Access to government services	$\text{GUBERN} = \dfrac{\#\text{ no National Identification (DNI for Peru)}}{pop.}$
Public spaces	PUBSPACE=# sites
Historic patrimony	PAT=# sites

Peruvian specific indicators, which include public spaces and historic patrimony, were taken from the Peruvian vulnerability assessment of Huaraz. These indicators are not normalized because they serve the entire community. Their location in the flood plain increases vulnerability because the community loses a site of importance. GLOF specific indicators such as sanitary services, communication and media, and access to government services were determined from assessing the unique impact a GLOF would have on Huaraz. GLOFs are sudden, catastrophic events that require advance warning for residents to evacuate the flood plain, government support, and robust public services and infrastructure (Hegglin & Huggel 2008).

Sanitary services: After a GLOF event a home's sanitary system may be destroyed or not work properly. Both scenarios can cause disease, particularly where underdeveloped sanitary systems are used. In addition poor sanitary services can indicate poor health or low income. The census divides sanitary systems into six categories, three of which are classified as no sanitary services: black well or latrine; river, ditch or channel; no sanitary system.

Communication and media: At present the city of Huaraz does not have a warning system to alert residents if a GLOF event occurs. Therefore other means of communication through which residents can learn about the risk of a GLOF or receive notification of a GLOF event are important. This indicator quantifies the number of electronic devices per person by which residents can access media with potential information regarding a GLOF event. The communication devices included in this indicator are described in Table 4.6.

Access to government services: The Huaraz census indicates how many people in a city block lack a national identification document. It is assumed that individuals without a national identification document will not be able to access government services and participate in relief programs in the aftermath of a GLOF.

Public spaces: The census provides information on the number of people that reside in each city block. Nonetheless the existence of public spaces in a block indicates that on certain occasions or times of day the population density of the area may increase significantly. Therefore city blocks with public spaces are considered more vulnerable. For this indicator the number of public spaces in each block was summed. Public spaces include schools (including universities), churches, markets, radio stations, athletic installations, healthcare facilities, and government offices.

Historic patrimony: Historic sites are linked to a community's identity and continuity over time. Huaraz experienced nearly total destruction of the historic city center in a 1941 GLOF and severe damage in the 1970 earthquake (INDECI 2003). Historic patrimony sites are considered vulnerable because of their importance for the community and scarcity. For this indicator the number of historic sites in each city block was summed. The sites included are cemeteries and huacas (Incan relics).

After defining and calculating each indicator described in Tables 4 and 6, the z-score for each indicator is calculated for each city block. Over 1200 city blocks were assessed in this analysis. The z-scores were calculated to normalize the data and avoid categories with larger scales dominating the vulnerability index. Equation 4.2 shows how z-scores were calculated. In Equation 4.2, x_n refers to vulnerability indicator n.

$$zscore = \frac{x_n - x_{n,avg}}{x_{n,stdev}} \qquad (4.2)$$

Next a principal component analysis (PCA) of the vulnerability indicators was conducted to reduce the dimensionality of the indicator to fewer independent (orthogonal) components that retain the variance of the original data set. Components are linear combinations of the original variables in the data set chosen such that the first component explains the largest amount of the variance of the data set. Subsequent components explain a decreasing portion of the data variance. (Johnson & Wichern 1982; Everitt & Hothorn 2011) The methodology results in a number of components equal to the number of variables in the data set. To reduce the dimensionality, the percent of variance explained criteria was used (Schmidtlein et al. 2008; Johnson & Wichern 1982). It is common to use the components that account for 76 to 90% of the total variance to replace the original dataset without significant loss of information (Johnson & Wichern 1982; Schmidtlein et al. 2008; Cutter et al. 2003).

Principal component analysis works best with data that is normalized (all data in the same scale) (Johnson & Wichern 1982) and centered. Z-scores adhere to both of these criteria (normalized and centered with an average of zero and variance of 1). (Schmidtlein et al. 2008) Although PCA provides best results for a normally distributed data set, normality is not a requirement for PCA (Johnson & Wichern 1982).

In order to align each component with the few variables on which it relies most, the Varimax rotation was used. Rotating factors are used to simplify the structure of the principal components and to facilitate interpretation of the components (Abdi 2003). Because some indicators are inversely related to vulnerability (e.g., socio economic status and communications and media), components that rely heavily on these indicators were assigned a negative value before aggregating in the vulnerability index. The Varimax rotation produces a solution where each component has a small number of variables with large weights and the other variables have zero weights (Abdi 2003). This rotation allows identification of components that are primarily composed of the indicators that decrease vulnerability.

Results

The results of the Huaraz social vulnerability analysis before reducing index dimensionality or conducting the Varimax rotation are presented on a map of the city in Figure 4.5. To estimate the social vulnerability shown in Figure 4.5, the z-scores are summed for each vulnerability indicator in Tables 4.4 and 4.6 for each city block.

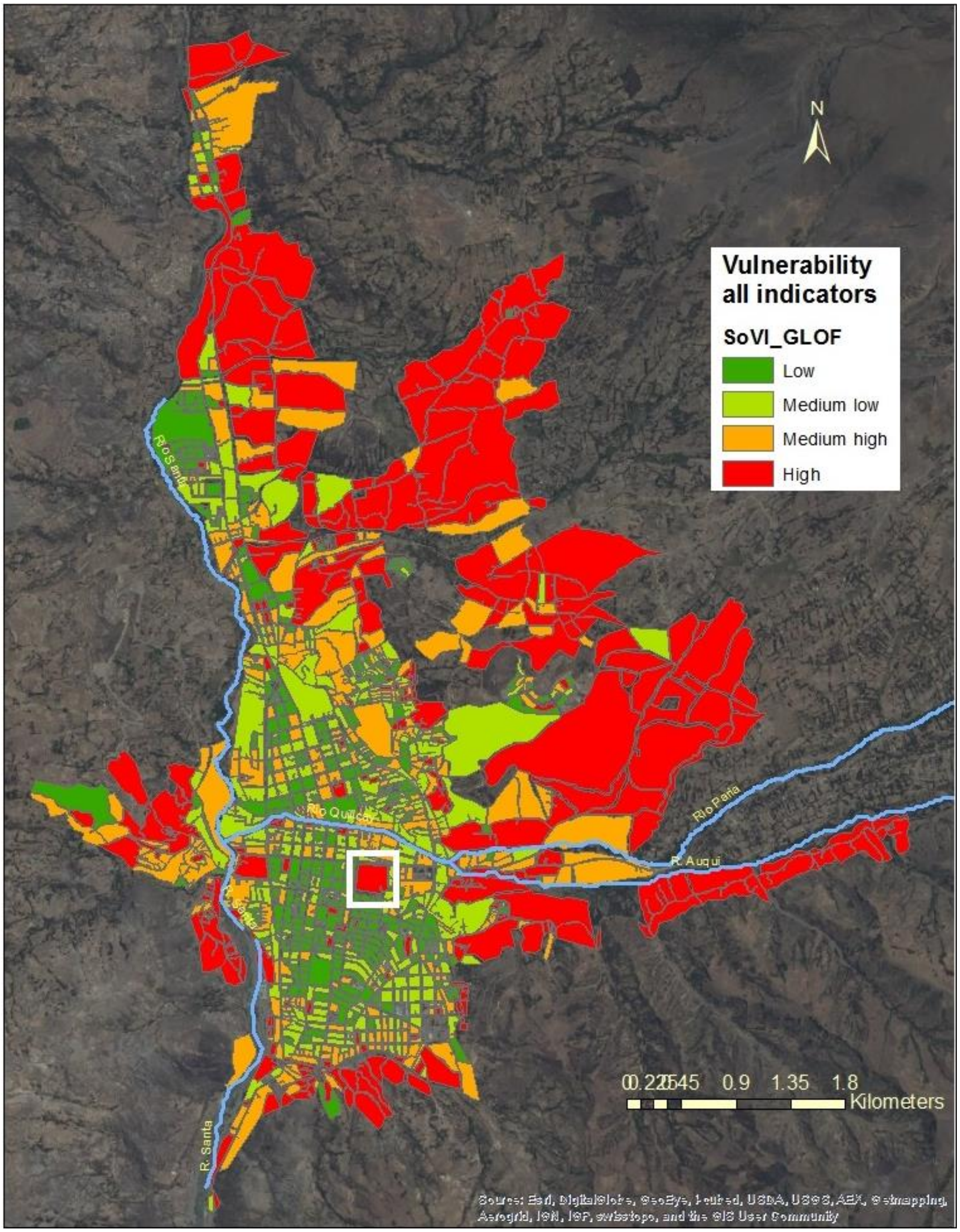

Figure 4.5. The mapped social vulnerability index for Huaraz shows areas of low vulnerability south of the River Quillcay, areas of medium vulnerability on the north and south edges of the river, and areas of high vulnerability on the periphery of the city.

To create the classifications denoted by colors in Figure 4.5, the vulnerability values were divided into quartiles. Therefore the red group represents the highest vulnerability quartile whereas the dark green reflects the least vulnerable 25% of the city. Given that the vulnerability assessment is relative in the context of the entire city, quantiles allow for the identification of city blocks that are relatively more or less vulnerable.

Figure 4.5 shows areas of high social vulnerability along the rivers leading into and out of the city. The south central area of the city, though, shows concentrations of low and medium low vulnerability whereas outlying areas of the city are mostly classified as high vulnerability. Overall, the vulnerability in the central areas of the city calculated here corresponds well to vulnerability classifications developed by the Peruvian government (2003) and Hegglin and Huggel (2008) (see Figure 4.6), although the Peruvian government results differ from the results in Figure 4.5 in the city outskirts. Nonetheless, vulnerability indicators summed to calculate the values in Figure 4.5 have not been screened for correlation. Therefore the results in Figure 4.5 may overestimate vulnerability when indicators are highly correlated.

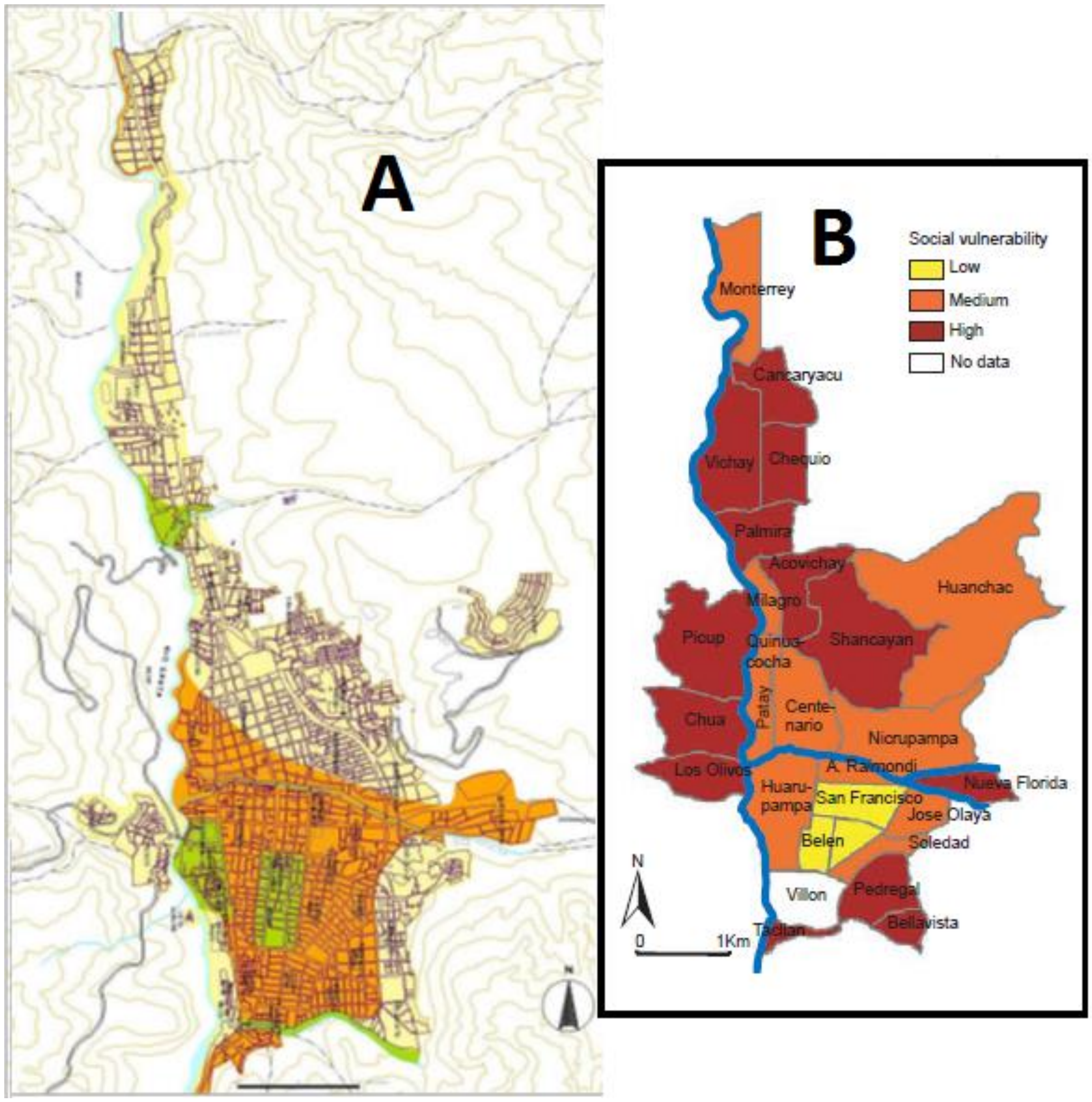

Figure 4.6. Social vulnerability assessments from the Peruvian government (A) and Hegglin and Huggel (2008). In the Peruvian government assessment social vulnerability is represented as very low (green), medium (yellow), and high (orange).

To minimize correlation in the indicators contributing to social vulnerability, a principal component analysis of the indicators was conducted. The methodology produced 16 orthogonal components resulting from linear combinations of the indicators described previously. Each component accounts for a decreasing proportion of the total variance of the data set. Table 4.7 contains a summary of the proportion of total variance in the data set that each component accounts for.

Table 4.7. Results from the PCA shows the proportion of variance and cumulative proportion of variance each component accounts for. Components are linear combinations of the vulnerability indicators described previously.

	Proportion of Variance	Cumulative Proportion of Variance
PC1	0.21	0.21
PC2	0.10	0.31
PC3	0.08	0.39
PC4	0.07	0.45
PC5	0.07	0.52
PC6	0.06	0.58
PC7	0.06	0.65
PC8	0.06	0.71
PC9	0.06	0.76
PC10	0.05	0.81
PC11	0.05	0.86
PC12	0.04	0.90
PC13	0.03	0.93
PC14	0.03	0.96
PC15	0.02	0.98
PC16	0.02	1.00

In order to reduce the dimensionality of the vulnerability index and minimize correlation in the data set, a subset of the 16 principal components must be chosen that account for 90% of the variance in the data set. The decision to use the components that account for 90% of the variance is based on guidance from literature sources (Johnson & Wichern 1982; Schmidtlein et al. 2008; Cutter et al. 2003; Everitt & Hothorn 2011).

The Varimax rotation was then applied to the 12 components to align each component with only a few indicators. The result of the rotation is a series of 12 components shown in Table 4.8.

Table 4.8. Components for vulnerability indicators after PCA and Varimax rotation. Highlighted cells represent the indicators contributing to each component.

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12
SOCIOECO	0	0	0	0	-0.2	0	0	0	0	0	-0.1	0.6
RACE	0.4	0.1	0	0	0	0.1	0	0	0	0	0.4	0
AGE	0	-0.7	0	0	0	0	0	0	0	0	0	0.1
EMPLOSS	0	0	0	0	0.9	0	0	0	0	0	0	0
RUUR	0	0	0	0	0	0	0	0	0	1.0	0	0
RESIPROP	0.7	0	0	0	0	0	0	0	0	0.1	-0.2	0
RENTERS	0	0	1.0	0	0	0	0	0	0	0	0.0	0
OCCUP	0	0	0	0	0	0	0	0	0	0	0.9	0
FAMSTRUC	0	-0.7	0	0	0	0	0	0	0	0	0.1	-0.1
SOCIDEP	0	0	0	0	0	0	0	1.0	0	0	0	0
SPENEEDS	0	0	0	1.0	0	0	0	0	0	0	0	0
SANITARY	0.6	0	0	0	0	0	0	0	0	-0.1	0.1	0
COMMUN	0	0	0	0	0.2	0	0	0	0	0	0	0.8
GUBERN	0	0	0	0	0	-1.0	0	0	0	0	0	0
PUBSPACES	0	0	0	0	0	0	0	0	-1.0	0	0	0
PATRIMONIO	0	0	0	0	0	0	1.0	0	0.0	0	0	0

The two indicators that are inversely proportional with social vulnerability, SocioEco and Commun, contribute to PC5, PC11, and PC12. In components 5 and 11, however, these indicators contribute a small amount compared with the other indicators. However, component 12 is largely composed of SocioEco and Commun indicators with other indicators contributing a small amount. Therefore this component (12) will be assigned a negative value.

Once all the indicators have been linearly combined into the components defined in Table 4.8, they are summed to calculate the vulnerability index. All components are added with a coefficient of one as was done by Cutter et al. (2003). The resulting vulnerability index is shown on a map of Huaraz in Figure 4.7. Figure 4.7 shows similar vulnerability regions as Figure 4.5, but overall the map shows more medium vulnerability regions in place of extremes (high or low).

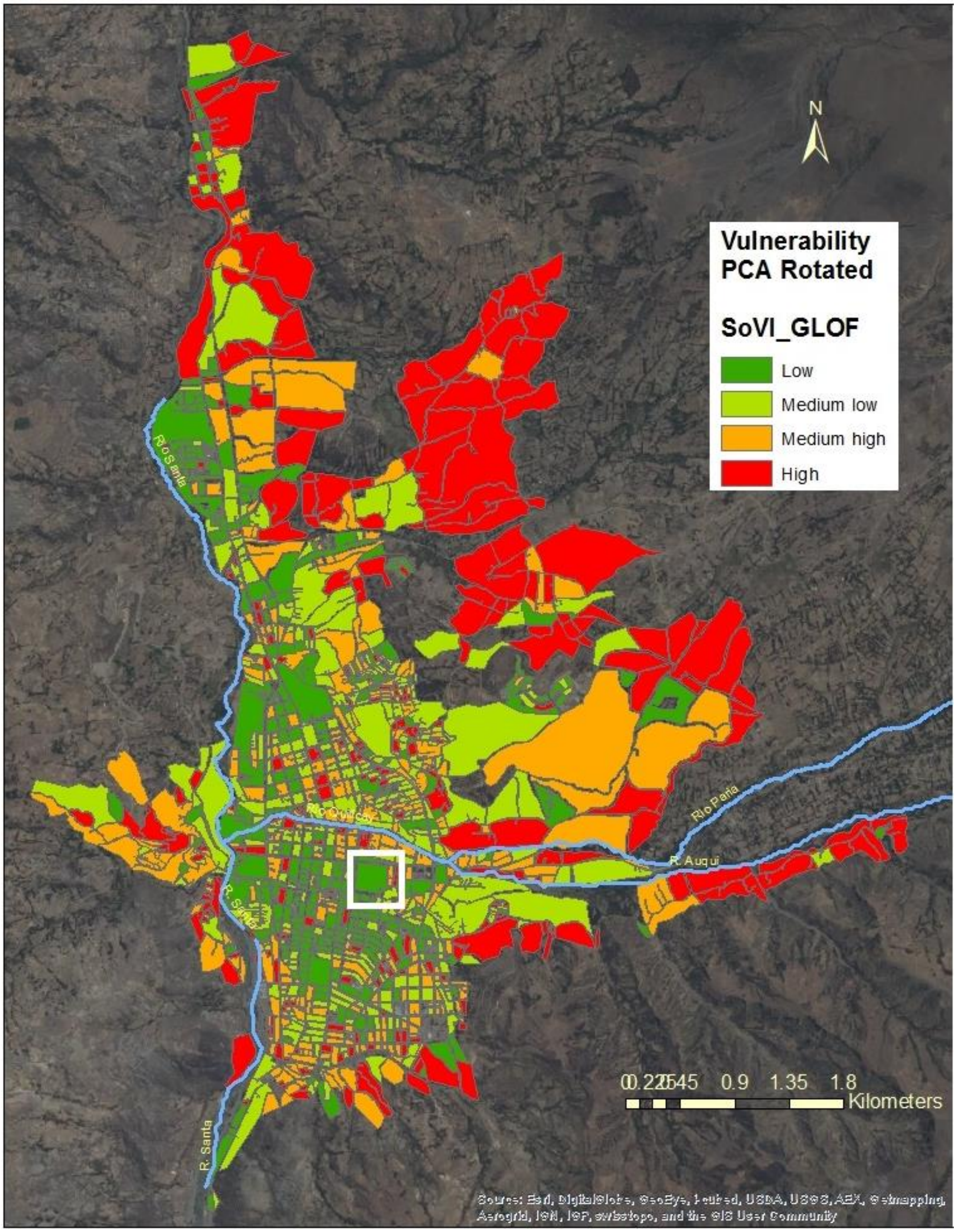

Figure 4.7. The vulnerability index after application of PCA and Varimax rotation shows areas of low vulnerability south of the River Quillcay, areas of medium vulnerability on the north and south edges of the river. Peripheral areas still show high vulnerability, though less severe than in Figure 4.5.

Somos-Valenzuela (2014) used the 2007 census data to also calculate the SoVI for the City of Huaraz. Somos-Valenzuela followed a similar procedure to calculate the SoVI as outlined here including use of PCA and the Varimax rotation. The main difference with the work presented here, however, is the use of different indicators and indicator definitions. Equations are not provided for the indicators used, therefore a clear comparison to the SoVI developed here is not possible. Despite the differences in indicator definition and the indicators included, the SoVI calculated by Somos-Valenzuela shows similar patterns of vulnerability in the GLOF flood plain (the region for which vulnerability was calculated) to those shown in Figure 4.7.

The vulnerability results in Figure 4.7 are consistent with vulnerability in the city center reported in the Peru (2003), Hegglin and Huggel (2008) (Figure 4.6), and Somos-Valenzuela (2014) studies, and with results for the city periphery reported by all studies except the Peru (2003) analysis. Therefore it can be tentatively concluded that the vulnerability index developed here reflects the actual vulnerability of the Huaraz population at the city block scale. Further expert verification is needed, however, to definitively conclude that the SoVI_GLOF is an accurate representation of vulnerability in Huaraz.

As a means of comparing the unrotated (all indicators shown in Figure 4.5) results with the rotated results in Figure 4.7, the city block indicated with a white square is assessed. This city block changes from high to low vulnerability after the PCA and Varimax rotation. Reviewing all 16 indicators from the unrotated data shows that this city block is in the top 50% (when sorted in ascending order) for all indicators except for RUUR (density), COMMUN (ownership of communication devices), and Race (native language speakers). Therefore the designation of high vulnerability in Figure 4.5 is indicative of this city block performing poorly in only 4 indicators, which dominates the relatively good performance for the remaining 12 indicators. After the PCA and Varimax rotation this city block is found to have low vulnerability, which is in keeping with the majority of the indicators for this block. Therefore it can be concluded that the PCA and rotation conducted here were successful in reducing the domineering effect of a few indicators on the aggregate index to better reflect the vulnerability of each city block.

The vulnerability results developed here will be included in the DEA portion of the economic analysis as part of the intangible consequences of a GLOF event. A detailed analysis of vulnerability inclusion in the DEA is included below.

Economic Analysis

The economic analysis compares the costs of lowering Lake Palcacocha to the benefits of decreased damage in Huaraz in the event of a GLOF. The objective is to assess the costs and benefits of the projects proposed for Lake Palcacocha (lowering by 0, 15, and 30 meters with and without EWS) while also taking into account uncertainty regarding the timing and occurrence of a GLOF. Through this analysis the value of intangible damages will be assessed both through literature sources and by inferring their value using DEA. This analysis will also assess whether projects are economically efficient in the DEA as well as the expected cost of the various projects using DA.

Data Envelopement Analysis (DEA)

DEA allows the analyst to determine the price of intangibles that would make a given project efficient, given that it lies on the efficient project frontier. As mentioned in the Methods section (Chapter 2), there are two approaches for conducting a cost benefit analysis using DEA. One developed by Womer et al. (2006) (abbreviated as the competitive equilibrium method), assumes that projects compete in a perfect market where they earn zero profits (competitive equilibrium), meaning that benefits must be able to balance costs. This method identifies the weight (price) for each intangible consequence that maximizes the profits (constrained to a maximum of zero) of the project being assessed subject to the constraint that all other projects have profits equal to or less than zero. Another method, developed by Kuosmanen and Kortelainen (2004) (abbreviated as the competitive advantage method), determines the price for intangibles that maximizes the competitive advantage of the project under analysis as compared to the next best option. In the competitive advantage method, the project being analyzed must have a positive social benefit (benefits minus costs; also referred to as net benefit). In the case of a GLOF from Lake Palcacocha a lake lowering project would only decrease the damage in Huaraz as compared to no lake lowering (business as usual or BAU). Therefore for the DEA the consequences of a GLOF after lake lowering are calculated relative to the BAU scenario since both DEA methods require projects to have benefits (positive consequences). Table 4.9 shows the consequences of a GLOF relative to the BAU scenario after each mitigation decision assessed here.

Table 4.9. Consequences of a GLOF from each size avalanche under the three GLOF mitigation decisions relative to the no lowering (BAU) scenario. Letters in parenthesis refer to variables in Equation 4.4.

Decision	Structure damage avoided	Life loss avoided (z)	Social risk avoided (z)	Project costs	Net benefits (B)
Large avalanche GLOF					
0m lower EWS	$0	3818	0	$2,000,000	-$2,000,000
15m lower	$5,208,850	2990	549	$3,750,000	$1,458,850
15m lower EWS	$5,208,850	5073	549	$5,750,000	-$541,150
30m lower	$10,472,511	3778	2325	$7,500,000	$2,972,511
30m lower EWS	$10,472,511	5498	2325	$9,500,000	$972,511
Medium avalanche GLOF					
0m lower EWS	0	154	0	$2,000,000	-$2,000,000
15m lower	$16,873,474	277	953	$3,750,000	$13,123,474
15m lower EWS	$16,873,474	277	953	$5,750,000	$11,123,474
30m lower	$18,867,222	284	1220	$7,500,000	$11,367,222
30m lower EWS	$18,867,222	284	1220	$9,500,000	$9,367,222
Small avalanche GLOF					
0m lower EWS	0	0	0	$2,000,000	-$2000000
15m lower	$2,087,310	5	151	$3,750,000	-$1,662,690
15m lower EWS	$2,087,310	5	151	$5,750,000	-$3,662,690
30m lower	$2,087,310	5	151	$7,500,000	-$5,412,690
30m lower EWS	$2,087,310	5	151	$9,500,000	-$7,412,690

It is important to remember that the first four columns are decreases in damages as compared to the no lowering scenario no EWS (BAU). Because a small flood does not cause flooding in Huaraz when Lake Palcacocha is lowered 15 or 30 m, the decrease in damage is the same for all decisions. Also, the EWS decisions only change the evacuation time available for residents and consequently fatalities. Therefore all damages other than loss of life are the same as the no EWS scenarios. Values in the structure damage columns were calculated as described in the HEC-FIA section of this chapter.

Total life loss was also estimated using HEC-FIA. The social risk score is explained below.

In this work the vulnerability index described above, SOVI_GLOF, was included in the DEA as an intangible score. This score is calculated by multiplying vulnerability (SoVI_GLOF) times a hazard index for each flood scenario studied here and summing the score for the affected area of Huaraz. Because vulnerability is a measure of the susceptibility of the population to harm from a GLOF event, vulnerability is multiplied by a measure of the severity of flooding at each block (hazard) to quantify the social risk (hazard times vulnerability is risk (Karmakar 2010; United Nations 2008)) from a GLOF.

To estimate the social risk score in Table 4.9 a hazard map was created using the results of the FLO-2D modelling of a GLOF and the definition of high, medium, and low hazard levels from Garcia-Martinez and Lopez (2007). Each hazard level is defined by the maximum depth of water and depth times velocity (d*v). The characteristics of each hazard level are given in Table 4.10.

Table 4.10. Hazard level for a debris flow from Garcia-Martinez and Lopez, 2007, HEC-FIA fatality zones and the fatality rate for each zone used as the numerical value for each hazard level.

Hazard level	Maximum depth (m)	d*v (m^2/s)	Garcia-Martinez & Lopez description	HEC-FIA fatality zone	Fatality rate (hazard index)
high	d>1.0	OR d*v>1.0	People: In danger inside and outside buildings Buildings: in danger of destruction	Chance zone: conditions where individuals are swept away or trapped underwater	0.91
medium	0.2<d< 1.0	AND 0.2<d*v<1.0	People: In danger outside Buildings: damage or destruction depending on construction	Compromised zone: severely damaged shelters provide limited protection	0.12
low	0.2<d<1.0	AND d*v<0.2	People: low to none Buildings: little damage	Safe zone: waters shallow	0.0002

Each hazard level in Table 4.10 is assigned to a fatality zone and fatality rate used in the HEC-FIA model, thereby assigning a numerical value (hazard index) to each hazard zone. The fatality rates from the HEC-FIA model were used as the hazard index because they describe the damage to individuals and their property when confronted with a flooding event of a given intensity. The fatality zone descriptions (more detail provided in the methods chapter) are given in Table 4.10 along with the fatality rate used as a hazard index in this study.

The hazard maps were overlain with the vulnerability map to determine the hazard level at each city block for the flood and lake lowering scenarios. Figure 4.8 shows the hazard map over the vulnerability map in Huaraz used in this study. As noted previously, the implementation of an EWS in Huaraz would not affect flooding and consequently social risk scores. Therefore the 0 m map in Figure 4.8 also represents the consequences for social risk with an EWS; the same applies to the other lowering and lowering with EWS scenarios studied.

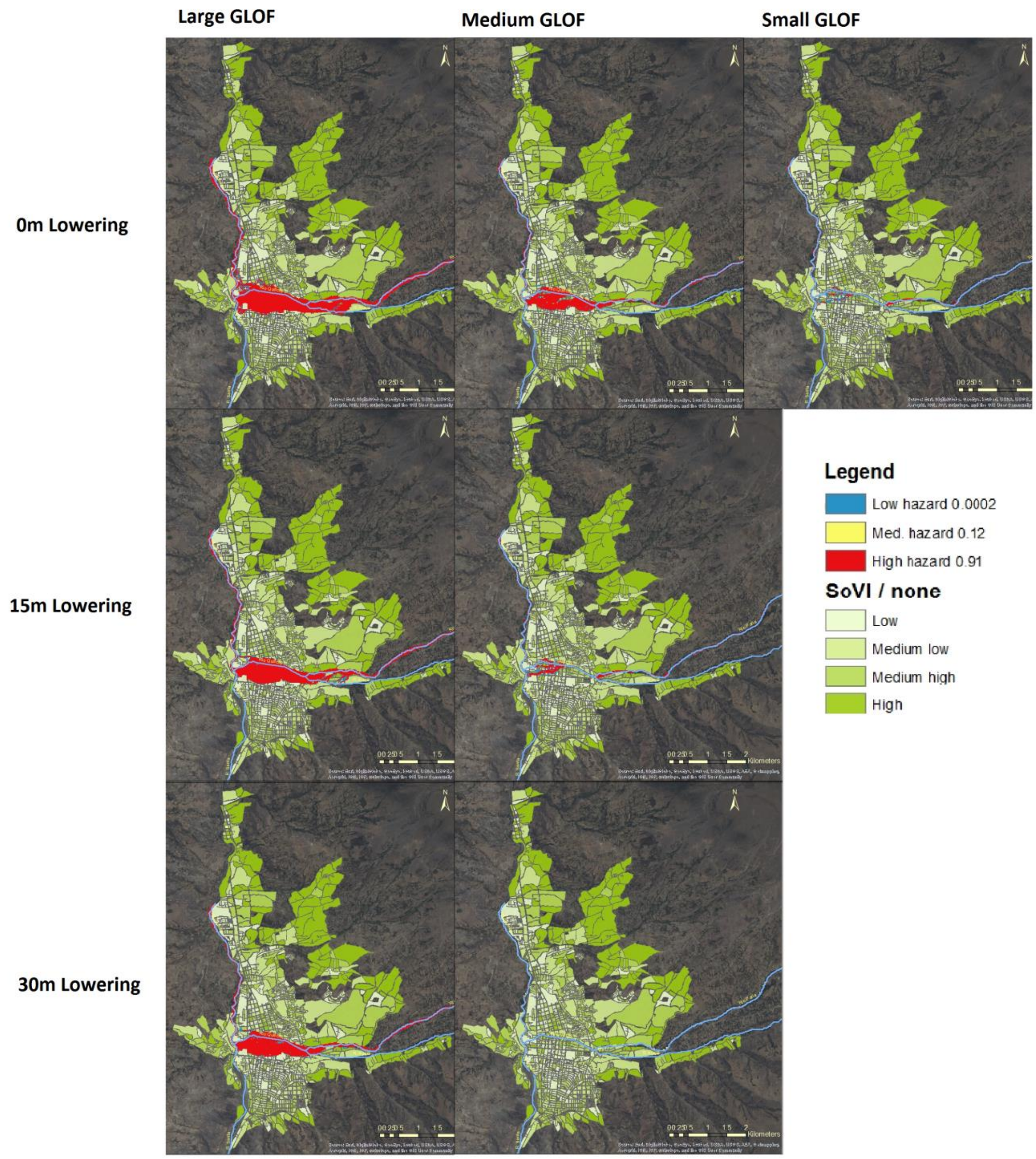

Figure 4.8. Hazard and vulnerability maps are shown for all Lake Palcacocha GLOF scenarios assessed.

The maps in Figure 4.8 were used to extract the hazard level and corresponding index (see Table 4.10) for each city block and multiply it by the vulnerability index value, which was scaled to have only positive values by adding the absolute value of the minimum vulnerability index value (-21). Then the social risk scores were summed over the entire city. The raw social risk scores are summarized in Table 4.11. Lower social risk scores in Table 4.11 indicate that mitigation measures resulted in lower damage to vulnerable populations in the event of a GLOF.

Table 4.11. Raw social risk scores for each lake lowering and GLOF trigger scenario.

Scenario	Social risk score
0m lower, large	2670
0m lower, medium	1298
0m lower, small	151
15m lower, large	2121
15m lower, medium	345
30m lower, large	1801
30m lower, medium	78

To obtain the values in Table 4.9 each score for the lake lowering scenario was subtracted from the corresponding scenario in terms of GLOF size with no lake lowering.

Costs for each lake lowering option and the EWS were calculated based on the estimate for lowering the lake 20 meters and reinforcing the terminal moraine provided by Cesar Portocarrero (Personal communication, 2016). According to a recent estimate, lowering the lake 20 meters would cost \$5 million. This estimate includes the lake lowering works, construction of a reinforced dam at the lake outlet, and a spillway. Additionally, an EWS for Huaraz has been priced and is estimated to cost \$2 million (C. Portocarrero, Personal communication, 2016). The estimates for 15 and 30 m lowering scenarios were linearly extrapolated from the 20 m estimate as shown in Equation 4.3.

$$Cost = \frac{\$5{,}000{,}000}{20m}(m\ of\ lowering) \qquad (4.3)$$

Net benefits in Table 4.10 are the sum of the benefits due to decreased building damage minus the project costs. Because the expense to lower the lake level is a cost, it is subtracted from the benefit of decreased building damage. Net benefits are used in the DEA rather than separate project cost and avoided damage benefit categories because monetary costs are assigned as the numeraire in the analysis. The numeraire has a coefficient of one and determines the units in which prices from the DEA are reported.

Because net benefits for several projects in the large and medium flood are positive, the competitive equilibrium method cannot be used for the DEA. The competitive equilibrium method requires that costs and benefits be balanced to give a total project value (profit) of zero. Balancing costs and benefits is not possible when all consequence categories have a positive value. Therefore the competitive advantage method for the DEA is used as shown in Equation 4.4.

$$\max_{p} \mathrm{CA_k} \tag{4.4a}$$

$$\mathrm{s.t.\,CA_k} \leq \left[\mathrm{B_k} + \sum_{m=1}^{M} \mathrm{p_m Z_{km}}\right] - \left[\mathrm{B_i} + \sum_{m=1}^{M} \mathrm{p_m Z_{im}}\right]$$

$$\text{for } \mathrm{i} = 1, \dots, \mathrm{k}-1, \mathrm{k}+1, \dots, \mathrm{N} \tag{4.4b}$$

$$\mathrm{B_k} + \sum_{m=1}^{M} \mathrm{p_m z_{km}} \geq 0 \tag{4.4c}$$

$$\mathrm{p} \geq 0 \tag{4.4d}$$

$$\text{Where: } \mathrm{CA_k} = \left[\mathrm{B_k} - \sum_{m=1}^{M} \mathrm{p_m Z_{km}}\right] - \left[\mathrm{B_i} - \sum_{m=1}^{M} \mathrm{p_m Z_{im}}\right] \tag{4.4e}$$

As mentioned in the Methods section (Chapter 2), DEA does not incorporate uncertainty in the timing, size, or occurrence of a GLOF. Therefore the DEA is conducted for each avalanche size to understand the efficient decision when a large, medium, or small GLOF from Lake Palcacocha occurs.

In the competitive advantage method a project is efficient if it has a positive value. The value is the competitive advantage of the project being analyzed compared to the next best project assessed. Maximizing the competitive advantage of a given project is analogous to the cost benefit analysis methodology which identifies the decision with the greatest benefits (Kortelainen & Kuosmanen 2004). In addition to the maximum competitive advantage, the competitive advantage method computes the weights or prices (p in Equation 4.4) for each non-tangible consequence that maximizes the competitive advantage. These values can be interpreted as how each project values intangible consequences. The results of the DEA for each possible GLOF size are given in Table 4.12.

Table 4.12. Results of the DEA for lowering Lake Palcacocha and a small, medium and large avalanche triggered GLOF.

Large avalanche GLOF			
Efficient project	Lower 30 m + EWS		
Value (CA_k)	unbounded		
Weights (p)	Net benefits	Loss of life ($/fatality)	Social risk score ($/unit)
	1	>$1,163	unbounded
Medium avalanche GLOF			
Efficient project	Lower 30 m		
Value (CA_k)	$2,000,000		
Weights (p)	Net benefits	Loss of life ($/fatality)	Social risk score ($/unit)
	1	$8,503	$13,834
Small avalanche GLOF			
Efficient project	Lower 15 m		
Value (CA_k)	$2,000,000		
Weights (p)	Net benefits	Loss of life ($/fatality)	Social risk score ($/unit)
	1	>$333,000	>$10,981

The results in Table 4.12 show that to protect against a small avalanche GLOF the efficient project with the greatest competitive advantage is to lower the lake 15 m. For the small GLOF, the maximum competitive advantage over the next best decision (lower 15 m + EWS) is $2,000,000, equal to the cost difference (the only difference between the two projects in terms of consequences) between the two decisions. Because the only difference between the 15 m lowering and 15 m lowering with EWS projects is the cost of the EWS, the competitive advantage is independent of the price assigned to LOL and social risk. Therefore the binding constraint is Eq. 4d stating that social benefit of the efficient project must be greater than zero. When LOL has a weight of $333,000 or greater (holding social risk weight at $0) and social risk has a weight of $10,981 or greater (holding LOL weight at $0) the social benefit of the 15 m lowering project is positive and the constraint in Eq. 4d is met.

In the event of a medium GLOF, the efficient option with the greatest competitive advantage is to lower Lake Palcacocha 30 m. Lowering the lake by 30 m instead of 15 m (closest competitor) results in a small decrease in fatalities (7 avoided fatalities) and a large decrease in the social risk score (267 improvement). Therefore the 30 m lowering decision results in greater weighting for the social risk score ($13,834) than for loss of life ($8,503).

In the event of a large GLOF lowering the lake 30 m and installing the EWS is the efficient decision with the maximum competitive advantage. Because adding the EWS system only decreases fatalities, the 30 m lowering and EWS decision has no competitive advantage over 30 m lowering (the next best decision) in terms of social risk. Therefore the price for social risk is unbounded. In addition, lowering the lake by 30 m + EWS gives a competitive advantage in terms of fatalities (LOL) over its nearest competitor (lowering the lake 30 m) while meeting the constraints of the competitive advantage method at any price greater than $1,163 for fatalities. Therefore the value (maximum competitive advantage) for the project is unbounded and lowering the lake 30 m + EWS is efficient at any weight for social risk and for valuation of fatalities greater than $1,163.

Overall the DEA competitive advantage method is well suited for assessing the efficiency and competitive advantage of GLOF mitigation projects proposed for Lake Palcacocha. Using the social risk score and total avoided fatalities, the DEA methodology takes into account intangibles without having to assign them a monetary value. Nonetheless, this analysis does not result in a unique solution for the price of intangibles for the small and large avalanche induced GLOF and does not account for uncertainty in the occurrence and timing of a GLOF. Uncertainty will be incorporated in the decision analysis in the next section. Additionally, the importance of the pricing of intangibles (social risk in particular since there is no guidance on pricing social risk in the literature) will be considered in the sensitivity analysis of the DA.

Decision Analysis (DA)

Unlike DEA, decision analysis incorporates uncertainty in the economic analysis. DA relies on a decision tree to map out the consequences of each decision (lake lowering projects in this case) and calculate the expected cost of a decision. The project with the lowest expected cost (greatest expected benefit) should be the preferred decision (Keeney 1982). It is possible to conduct the DA with benefits using relative benefits as compared to the BAU scenario as shown in Table 4.9. However, in order to clearly express the consequences of each decision, this analysis uses total consequences instead of relative values. Although all decisions presented here only have costs, the benefit of any mitigation project is a decrease in damages and costs as compared to the current state of Lake Palcacocha (BAU). Figure 4.9 shows the decision tree for the decision analysis of Lake Palcacocha GLOF mitigation projects.

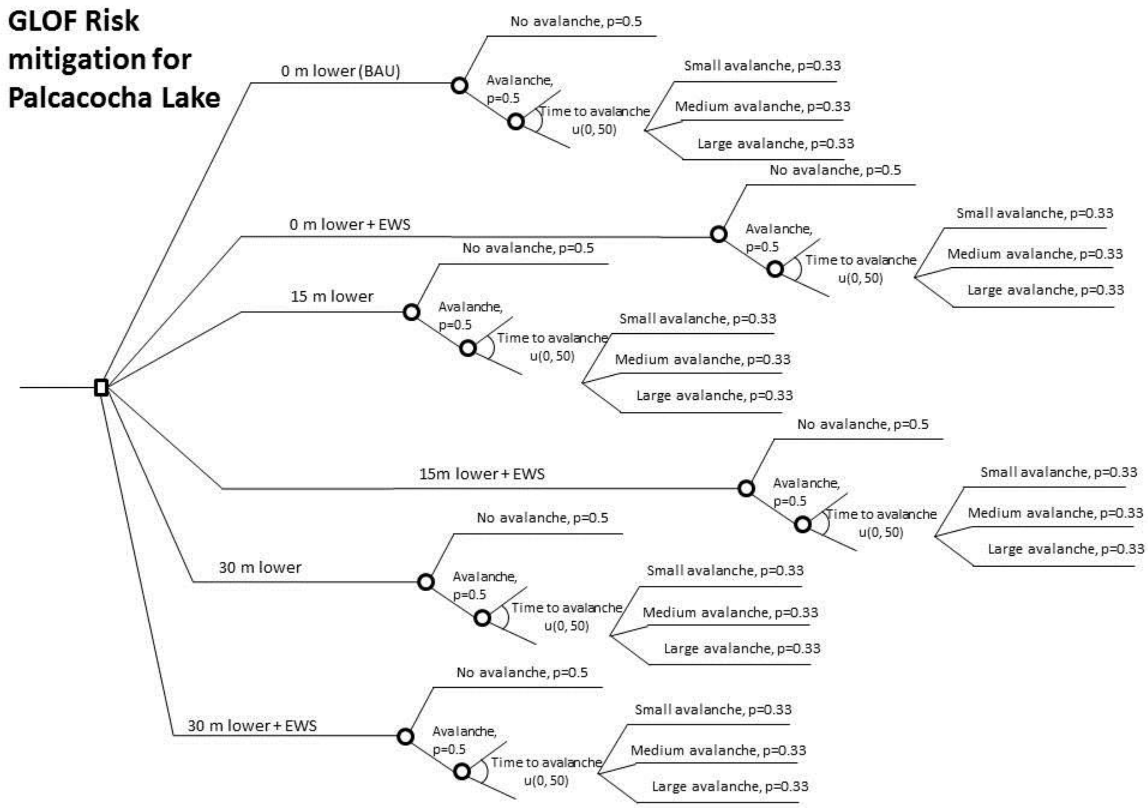

Figure 4.9. Decision tree for Lake Palcacocha GLOF mitigation projects.

At present very little is known about the likelihood and timing of the various GLOF (avalanche) scenarios. To reflect the high uncertainty surrounding a GLOF from Lake Palcacocha diffuse probability distribution (equal probability for all avalanche scenarios) is used for the likelihood and size of an avalanche resulting in a GLOF. A uniform distribution is also used for the timing of a GLOF, meaning that a GLOF is equally likely to occur in any year over the next 50 years. The decision to use a diffuse probability distribution for all uncertain variables stems from the Information Theory concept of entropy which shows that assigning two events equal probability has the greatest entropy and therefore relies only on the (minimally) available information. (Jaynes 1957)

Despite using a diffuse probability distribution, the decision tree in Figure 4.9 makes assumptions regarding the probability and likelihood of a GLOF event. The decision tree maximizes the uncertainty of a GLOF event and timing by using diffuse probability distributions in each chance node of the decision tree. Alternatively, a decision tree could be developed that maximizes the uncertainty of the outcomes of each decision. Such a tree would assign equal probability to each consequence (for example, all GLOF scenarios would have 0.25 probability and the distribution of the time to an avalanche distribution would be such that the net present cost of a GLOF would be the same, regardless of the timing of the event). In this case, the decision tree was structured to represent the uncertainty that exists at every chance node, which acknowledges the possibility of the scenarios shown, but assumes no further knowledge of their likelihood. Another assumption in the decision tree is that only one avalanche will occur in the 50 year lifetime modeled. A recent study reports that a small avalanche is more likely to occur and may occur with more frequency than larger avalanches (Somos-Valenzuela et al. 2016), however the exact probability or frequency is unknown. By modeling one event, however, this work estimates consequences for the best case scenario where only one small, medium and large avalanche can occur in the next 50 years. Techniques such as Bayesian updating could be used to update the information in Figure 4.9 as new knowledge is generated about the probability and timing of the scenarios shown.

To determine the timing of a GLOF the expected lifetime of the mitigation projects was used. For concrete structures (dyke and spillway) the lifetime is 50 years, although older lake lowering projects in the Cordillera Blanca show signs of surpassing the 50 year design lifetime (C. Portocarrero, Personal Communication, 2016). This study, however, will use the 50 year design lifetime; the expected value of a uniform distribution over 50 years is 25 years.

With each year of the 50 year life that it takes for a GLOF to occur the monetary damages need to be discounted to present value. A 6.6% annual discount rate is used here. The 6.6% discount rate is in keeping with recommendations from the US Office of Management and Budget (OMB). In conducting cost benefit analyses, the OMB recommends that government agencies discount future costs and benefits at the same rate a typical saver would use to discount future benefits. If the policy primarily affects consumption by the individual, the recommended discount rate corresponds to the real return rate of long term government bonds (3% in the U.S.). When private capital is affected by a policy the recommended discount rate is the average return rate of capital in the US economy before taxes, about 7% in the U.S. (OMB 2003) The Central Reserve Bank of Peru reports that the average corporate loan rate in April of 2016 was 6.38% and the loan rate for big companies was 7.24% (Central Reserve Bank of Peru 2016). In addition, the 9 year bond yield for Peru government bonds is 6.224% in April of 2016 (Investing.com 2016). Given that the share of individuals versus private capital that will be affected by a GLOF is unknown, the average of these three values (6.6%) is used as the discount rate in this analysis.

The decision analysis methodology requires that all consequences of a decision be valued in the same units, including intangibles. For this analysis, monetary values for all consequences are used except for social risk. Vulnerability, the indexed value in social risk, is an intangible consequence and no guidance exists on how to value it in monetary terms. To estimate the value of life loss, the value of a statistical life (VSL) from the US

Department of Transportation, \$9.1 million in 2012, is used. Because income in Peru is much lower than in the US, the VSL in Peru can be estimated using the ratio of real income in Peru to that in the US (Cropper & Sahin 2009). The World Bank's estimate of the Gross National Income per capita adjusted to ensure purchasing power parity for the US and Peru (The World Bank 2014) is used to adjust VSL for Peru. Purchasing power parity adjustments ensure that the income in a given country would allow an individual to consume the same kinds and quantity of goods in another country. This adjustment ensures that the VSL conversion reflects the goods (utility) that a Peruvian consumer would be willing to trade for a decrease in the risk of death. The adjusted VSL for Peru is \$1.7 million.

Using the adjusted VSL for Peru and fatality estimates from HEC-FIA (Table 4.2), the monetary cost of life loss from a GLOF was estimated. The other consequence from a GLOF that can be expressed in monetary terms is structure damage. A high and low value for structure damage was estimated previously (see Table 4.3) using estimates for home size and construction costs in Huaraz. The monetary consequences of each decision and GLOF scenario are shown in Table 4.13.

Table 4.13. Consequences for each decision and GLOF scenario in monetary units.

(1) Scenario	(2) Structure damage low	(3) Structure damage high	(4) Total life loss ($)	(5) Project costs
0 m lower, large	$43,435,146	$307,987,713	$10,689,818,951	$0
0 m lower, medium	$20,261,249	$143,667,431	$502,639,650	$0
0 m lower, small	$2,087,310	$14,800,594	$8,726,383	$0
0 m lower EWS, large	$43,435,146	$307,987,713	$4,026,353,032	$2,000,000
0 m lower EWS, medium	$20,261,249	$143,667,431	$233,867,059	$2,000,000
0 m lower EWS, small	$2,087,310	$14,800,594	$8,726,383	$2,000,000
15 m lower, large	$38,226,296	$271,053,067	$5,471,442,026	$3,750,000
15 m lower, medium	$3,387,775	$24,021,864	$19,198,042	$3,750,000
15 m lower, small	$0	$0	$0	$3,750,000
15 m lower EWS, large	$38,226,296	$271,053,067	$1,836,030,945	$5,750,000
15 m lower EWS, medium	$3,387,775	$24,021,864	$19,198,042	$5,750,000
15 m lower EWS, small	$0	$0	$0	$5,750,000
30 m lower, large	$32,962,634	$234,763,967	$4,096,164,094	$7,500,000
30 m lower, medium	$1,394,027	$9,884,698	$6,981,106	$7,500,000
30 m lower, small	$0	$0	$0	$7,500,000
30 m lower EWS, large	$32,962,634	$234,763,967	$1,094,288,405	$9,500,000
30 m lower EWS, medium	$1,394,027	$9,884,698	$6,981,106	$9,500,000
30 m lower EWS, small	$0	$0	$0	$9,500,000

To solve the decision tree in Figure 4.9 the consequence cost estimates in Table 4.13 are combined with the probabilities in each branch of the decision tree as shown in Equation 4.5.

$$EV = -\left(\frac{P_{GLOF}\,(\sum P_{size} Damages_{\Pr oject})}{(1+r)^t} + \frac{P_{NoGLOF}\,(\sum Damages_{\Pr oject})}{(1+r)^t} + C_{\Pr oject} \right) \tag{4.5}$$

In Equation 4.5 *EV* is the expected value for a given project, P_{GLOF} is the probability of a GLOF occurrence (50%), P_{size} is the probability of a GLOF of each size occurring (33%), $Damages_{project}$ refers to the values in columns 2 to 4 of Table 4.13 for the corresponding scenario, *r* refers to the discount rate (6.6%), *t* to the expected time to a GLOF occurrence (25 years) and $C_{project}$ is the cost of project implementation (column 5 of Table 4.13). In this analysis the low structure damage (column 2 of Table 4.13) was used in Equation 4.5 to calculate the lowest expected cost. If lake lowering is warranted under the lowest cost for building damages, then the decision holds for the high cost estimate as well. Using Equation 4.5 for each branch of the decision tree, the expected cost of each decision is computed as shown in Table 4.14.

Table 4.14. Expected cost of each lake lowering decision presented in Figure 4.9.

Decision	**Expected cost**
0 m lowering	$379,949,362
0 m lowering + EWS	$147,677,558
15 m lowering	$190,310,954
15 m lowering + EWS	$69,716,123
30 m lowering	$147,026,543
30 m lowering + EWS	$47,796,054

It is important to note that the values in Table 4.14 are costs and the lowest cost decision (lowering the lake 30 meters) is the preferred project in the DA method. The results in Table 4.14 also show that the value of the EWS is given by the difference between the expected cost of a given lake lowering project with and without the EWS. The value of the EWS for each lake lowering option is given in Table 4.15.

Table 4.15. Value of the EWS was calculated from the expected cost of each lake lowering decision with and without EWS.

	EWS Value
0 m lowering	$232,271,804
15 m lowering	$120,594,831
30 m lowering	$99,230,489

The results in Table 4.15 show that the value of the EWS decreases as the amount of lake lowering increases. Returns from the EWS decreases because greater lake lowering results in a slower moving flood and more evacuation time. Nonetheless, Table 4.15 shows that the value of the EWS far exceeds its cost ($2,000,000) for all lake lowering options.

In order to determine the robustness of the DA result to changes in uncertain variables a sensitivity analysis was conducted by changing the value of one parameter while maintaining the other parameter values constant. Each parameter value was changed such that the expected value of the lowest cost option (lowering 30 m) equals that of another project (the next lowest expected cost project, 15 m lowering + EWS). A conventional sensitivity analysis would perturb each variable by a given amount and determine the effect on the result. In this case the result of the DA is the lowest expected cost decision. Because the lowest cost decision is the most extreme GLOF mitigation option, perturbing the input variables such that the expected GLOF consequences increase will not change the lowest cost decision and provides no additional information. Therefore, a more informative approach to the sensitivity analysis is to determine what value for the uncertain variables will decrease expected consequences sufficiently to change the lowest cost decision.

The sensitivity analysis was conducted by changing one variable at a time for all variables except probability of a GLOF and probability of a small GLOF. For probability of a given GLOF (avalanche) size, the small GLOF probability was varied while the remaining probability was equally divided between the medium and large GLOF (probabilities must sum to 1). Likewise, the probability of a GLOF was varied and probability of no GLOF was calculated as one minus the resulting probability of a GLOF. The results of the sensitivity analysis are shown in Table 4.16.

Table 4.16. The sensitivity analysis for the decision analysis found the value of each parameter that changes the lowest expected cost decision.

Parameter changed	Value of parameter	New decision
Prob. of a GLOF	0.07	15m lower EWS
Prob. of a small GLOF	0.90	15m lower EWS
VSL adjusted Peru	$240,613	15m lower EWS
Discount rate	0.15	15m lower EWS
Time to flood	55	15m lower EWS

The sensitivity analysis shows that significant changes (upwards of 80% of the original value) in the parameters used to solve the decision tree are needed to change the lowest cost decision (lower the lake 30 m + EWS). The low sensitivity of the lowest cost decision to the uncertain parameters results from the high damage from a large GLOF even with lake lowering, which more than justifies the cost of the most extreme risk mitigation option. Installing the EWS with 15 m of lake lowering equals the expected cost of lowering Lake Palcacocha 30 m and installing the EWS when the probability of a GLOF is less than 7%, probability of a small GLOF is greater than 90%, value of a statistical life is less than $240,600, the discount rate is greater than 15%, or expected time to a flood is greater than 55 years (meaning that the time to flood is uniformly distributed over 110 years).

In the case of Lake Palcacocha the decision to lower the lake level is justified by high fatalities and building damage in Huaraz despite the uncertainty over the timing, occurrence, and size of a GLOF. A GLOF from Lake Palcacocha would result in high hazard flows in the center of the city and population. Therefore the least expected cost decision for mitigating the damage of a potential GLOF is to lower the lake 30 m and install an EWS, the most extreme option assessed. However, if the uncertain variables used to solve the decision tree (summarized in Table 4.16) are very different from those used here, the lowest cost decision may change. Lowering the lake 15 m and installing the EWS is the next lowest cost decision.

A greater case for lake lowering can be made if social risk is included in the DA. Although this approach has not been used in the literature, social risk can be valued using the results from the DEA. Table 412 shows that the medium avalanche case results in a weight of $13,834 for social risk. This weight complies with the result from the small avalanche GLOF (>$10,981) and the result from the large avalanche GLOF (unbounded valuation). Social risk is incorporated into the DA by multiplying the social risk score (Table 4.11) for each scenario by $13,834 and including it as a consequence in the DA. The expected cost for each scenario including social risk is shown in Table 4.17.

Table 4.17. Expected cost for all GLOF risk mitigation decisions including social risk.

Decision	Expected cost
0m lowering	$381,871,489
0m lowering EWS	$149,599,685
15m lowering	$191,461,587
15m lowering EWS	$70,866,756
30m lowering	$147,903,167
30m lowering EWS	$48,672,678

The results in Table 4.17 show that 30 m lowering with the EWS is the lowest cost decision followed by 15 m lowering with the EWS. The inclusion of social risk increased the damages from a potential GLOF, thereby further justifying GLOF mitigation works. A sensitivity analysis is not conducted for the weight of social risk since the DA without social risk showed that the lowest cost decision (lowering 30 m + EWS) does not change even when social risk is valued at zero.

DEA with expected damage values

In this section DEA is combined with expected damage values to incorporate uncertainty into the efficiency and intangible economic analysis conducted using DEA. To do so the uncertainty variables shown in the decision tree (probability of a GLOF, probability of GLOF size, time to a GLOF) as well as the discount rate described in the previous section are used to calculate the expected damage from a GLOF under each lowering decision. Monetary damages are adjusted using the likelihood of a GLOF (50%), likelihood of a given GLOF size (33%), and discounted using the time to a flood (25 years) with the discount rate (6.6%) as shown in Equation 4.6a. Non-monetary (intangible) damages are combined using the probability of a GLOF and GLOF size but are not discounted (see Equation 4.6b). Project costs would occur in the present and are not uncertain; therefore they remain unchanged from Table 4.9.

$$EV_{monetary} = \frac{P_{GLOF}\,(P_{size}C)}{(1+r)^t} \tag{4.6a}$$

$$EV_{intangible} = P_{GLOF}\,(P_{size}C) \tag{4.6b}$$

In Equations 4.6a and 6b, EV is the expected value of monetary or intangible consequences, P_{GLOF} is the probability of a GLOF, P_{size} is the probability of a given size of avalanche (GLOF trigger), and C refers to consequences of a GLOF. The term r in Equation 4.6a refers to the discount rate and t is the time to a GLOF. The expected value of damages from a GLOF are given in Table 4.18.

Table 4.18. Expected consequences of a GLOF for each decision available.

Decision	Expected LOL	Expected Stru. Damage	Expected Social Risk	Project Costs	Expected net Benefits
0 m lower	216	$10,963,951	139	$0	-$10,963,951
0 m lower + EWS	82	$10,963,951	139	$2,000,000	-$12,963,951
15 m lower	106	$6,935,679	83	$3,750,000	-$10,685,679
15 m lower + EWS	36	$6,935,679	83	$5,750,000	-$12,685,679
30 m lower	79	$5,726,110	63	$7,500,000	-$13,226,110
30 m lower + EWS	21	$5,726,110	63	$9,500,000	-$15,226,110

Expected damage values are then used to estimate the relative expected damages by subtracting damages for each lowering decision from the zero lowering (BAU) case. The relative expected damage values are shown in Table 4.19.

Table 4.19. Relative expected damages of a GLOF for each decision used in the DEA with expected values.

Decision	Structure damage	Total life loss	Social Risk	Project costs	Net benefits
0 m lower + EWS	$0	134	0	$2,000,000	-$2,000,000
15 m lower	$4,028,272	110	56	$3,750,000	$278,272
15 m lower + EWS	$4,028,272	181	56	$5,750,000	-$1,721,728
30 m lower	$5,237,841	137	76	$7,500,000	-$2,262,159
30 m lower + EWS	$5,237,841	195	76	$9,500,000	-$4,262,159

Using the values in Table 4.19 the DEA was conducted using the competitive advantage method. The results of the DEA are shown in Table 4.20.

Table 4.20. The DEA with expected damage values for each mitigation project shows that lowering the lake 30m is the efficient decision.

Efficient project	Lower 30 m + EWS		
Value	Unbounded		
Weights	Monetary costs	Loss of life ($/fatality)	Social risk ($/unit)
	-1	≥311,670	any

Using expected consequences from each lake lowering scenario in DEA shows that lowering Lake Palcacocha 30 m and installing an EWS is the efficient decision and has the maximum competitive advantage. The logic behind this result is similar to that behind the result of the large GLOF explained above. As in the large avalanche triggered GLOF DEA, 30 m lowering with EWS has no competitive advantage over the next best project (30 m lowering alone) in terms of social risk, which is why the weight for social risk is unbounded. At a price for loss of life (LOL) greater than $311,670 the constraints of the competitive advantage method are met and the 30 m + EWS decision has a competitive advantage over 30 m lowering alone. The value of the result is unbounded because LOL does not have a unique weight.

CONCLUSIONS

In this work the GLOF decision making methodology was applied to Lake Palcacocha in Peru. Likely GLOF scenarios were identified, their damage estimated, and it was found that damages from a potential GLOF to Huaraz city are sufficient to justify the cost of GLOF mitigation works to decrease damage to property and inhabitants. According to the DEA methodology, the efficient decision depends on the GLOF size analyzed. When the consequences of a small and medium GLOF are assessed, the efficient decision with the maximum competitive advantage is to lower the lake 15 m and 30 m, respectively. When assessing a large GLOF the efficient decision with the maximum competitive advantage is to lower the lake 30 m and install an EWS. The DA methodology shows that considering uncertainty in GLOF occurrence, timing, and size results in the 30 m lowering + EWS decision having the lowest expected cost. This analysis considers all GLOF sizes and is consistent with the DEA solution that also considers all GLOF sizes (DEA using expected values shows that 30 m + EWS is the efficient decision). Given that lowering the lake 30 m + EWS is an efficient decision from the DEA for a large GLOF and the lowest cost decision from the DA, this action is recommended as the best decision to mitigate the risk posed by a GLOF from Lake Palcacocha.

This analysis successfully adapted an existing dynamic flood fatality model to the structure and population characteristics of Huaraz and estimated damage to buildings and people. The consequence estimation portion of this analysis showed that a large GLOF from Lake Palcacocha would result in significant fatalities and damage to structures. Although lowering the lake level decreases damages in Huaraz, the flood's trajectory through the center of the city results in significant damage even when the lake is lowered 30 m.

For the Lake Palcacocha analysis the competitive advantage DEA methodology was used because several scenarios had net positive monetary costs. The competitive advantage DEA methodology was well suited for the analysis and provided clear results.

The DA portion of this work estimated the expected cost of each proposed mitigation project taking into consideration only consequences that can be valued in monetary terms. The lowest expected cost decision is to lower the lake 30 m and install the EWS. The sensitivity analysis showed that this decision holds even when large changes are made to the uncertain variables change. Incorporating social risk into the DA adds to the justification for 30 m lake lowering + EWS.

To combine the DA (incorporating uncertainty) and DEA approach, a DEA was conducted using expected values for the consequences from each decision. This approach resulted in 30 m lowering + EWS being the efficient decision. By combining the DEA and DA approaches the shortcomings of both methods were addressed. Nonetheless, the 0 m lowering scenario could not be assessed and the result of the expected value DEA should be considered in the context of the DA results.

Future work should focus on a better understanding of the vulnerability of populations in the flood plain. Even if Lake Palcacocha is lowered by 30 m and the EWS is installed, over 600 people may suffer fatalities and over 120 city blocks will be inundated in the event of a large GLOF (Table 4.2). By collecting updated information about the population at risk and better understanding their vulnerability to a GLOF event, local authorities can take additional measures to mitigate the social damage of a GLOF. Because a GLOF would flood the center of Huaraz, mitigation works at Lake Palcacocha are unlikely to eliminate damage to the city. Nonetheless, by addressing the social vulnerability of at risk populations, physical and social damage in the city can be minimized.

Chapter 5: Conclusion

OBJECTIVES FULFILLED

Three objectives were set out for this work in the introduction chapter. This dissertation fulfills the introduction objectives as outlined below:

(1) To identify potential flooding scenarios: In this work literature sources were used to establish the mechanism by which the two lakes studied (Imja Lake and Lake Palcacocha) could produce a GLOF. Collaborators were able to simulate the chain of events or single event that would cause a GLOF and estimate flood characteristics in nearby population centers with and without mitigation works at each lake. These scenarios were used in the GLOF decision making methodology.

(2) To evaluate the consequences of flooding scenarios: This objective was fulfilled at both locations studied but constrained by data availability. At the low data location (Imja Lake, Nepal), the data available included the location and type of buildings in the flood plain and number of inhabitants. Literature sources also provided estimates for the agricultural land in the flood plain and location of important trekking trails. In the high data location (Lake Palcacocha in Peru), a 2007 census of the city of Huaraz provided detailed information on the inhabitants of the flood plain as well as the location, number, and type of residences. This information was used to estimate fatalities and damage to buildings and infrasturcutre. At the Peru site the detailed demographic data allowed for estimation of social vulnerability in addition to fatalities and structure damage.

(3) A nuanced economic analysis of flood consequences and adaptation options: For both locations studied the DEA and DA methodologies were used to weigh the costs and benefits of the GLOF mitigation works assessed. The DEA methodology allowed for the inclusion of intangible GLOF consequences without assigning them a monetary value. Although the DA methodology required that all consequences be estimated in the same units (monetary), this methodology allowed for the inclusion of uncertainty in terms of the timing and likelihood of a GLOF. These two methodologies provided a means to compare the costs and benefits of GLOF mitigation works in a rigorous manner.

SITE SPECIFIC CONCLUSIONS

The GLOF decision making methodology was successfully applied to two glacial lakes with differing level of data availability. Imja Lake, in the Himalaya of Nepal, was a low data site due to the lack of detailed census information for the communities downstream of the lake. In contrast Lake Palcacocha lies upstream of a major city in the region (Huaraz) and the government conducted a detailed census of the population downstream of the lake in 2007. Detailed results for both of the sites where the decision making methodology was applied are given below.

Imja Lake, Nepal

The data available for Imja Lake and the community of Dingboche allowed for the estimation of fatalities and infrastructure damage (structures, agricultural land, and trekking trail) from a potential GLOF with and without a lake lowering project. Estimates of the potential damages from a GLOF were compared with the cost of lake lowering works using the DA and DEA methodology. The results show that lowering Imja Lake by 10 m is the lowest expected cost decision and also an efficient decision. Nonetheless, the sensitivity analysis shows that if costs for damages or damages themselves are less than those estimated here, the lowest cost decision may change. Additionally, the result is sensitive to small changes in the decision tree variables. Therefore it is recommended that decision makers assess the assumptions made in this analysis and update the analysis with any new information before proceeding with the recommended decision.

Lake Palcacocha, Peru

As mentioned previously, the availability of detailed census information for Huaraz City allowed for a more sophisticated assessment of damages due to a GLOF. Using the damage results in the DEA and DA methodology shows that lowering the lake 30 m and installing an early warning system (EWS) for a GLOF is the lowest cost decision. The 30 m lowering and EWS decision is also an efficient decision when DEA is used for the expected GLOF event. This decision is robust to large changes in the assumptions made in valuing intangibles and for the decision tree variable. In the case of Lake Palcacocha, the flood plain runs through the middle of an urban region resulting in significant damage. Because of the significant damage from a large GLOF, the cost of lake lowering works and an early warning system are justified by the damage avoided. Therefore taking action to mitigate the risk of a GLOF from Lake Palcacocha is strongly recommended.

SOURCES OF UNCERTAINTY

It is important to recognize the many sources of uncertainty in this analysis. Although the methods used in this analysis allowed for the implementation of the decision making methodology, the data and analysis used in this work has many sources of uncertainty.

The scenario analysis portion of this work required that the likely GLOF trigger and its characteristics be identified. In addition, results for the hydrodynamic modeling of each GLOF scenario was used to determine the impact in downstream communities with and without lake lowering. There are several sources of uncertainty in this portion of the analysis including identification of the GLOF trigger, prediction of the characteristics of the GLOF trigger, as well as the use of parameters and simplifications in the lake and GLOF flow modeling to make the analysis manageable. An assessment of the effect of these sources of uncertainty on the results of the hydrodynamic analysis can be found in the publications detailing this work; namely Somos-Valenzuela et al., 2016 and Somos-Valenzuela et al., 2015.

As noted above, estimating the consequences of a GLOF also requires several assumptions that contribute uncertainty. Both in Dingboche and Huaraz the resistance of buildings to flood waters is unknown. Therefore building damage estimates are approximations based on the characteristics of buildings in the US (Huaraz) or on the assumption that the buildings will not withstand flood waters (Dingboche). In addition the fatality rates used for the Nepal site were estimated from historical floods, none of which occurred in Nepal. Therefore the fatalities estimated here are uncertain. In Peru, the fatality estimate for a Lake Palcacocha GLOF relies on evacuation and fatality modeling developed for populations in the US and may not reflect the behavior of a Peruvian population. The timing of a GLOF warning with and without the EWS was modeled using warning dissemination curves for a US population and an estimate for when the population would become aware of an imminent flood, which adds uncertainty in the consequence estimation section. Finally, the vulnerability assessment was conducted using census data from 2007, which introduces uncertainty since the characteristics of the population has likely changed in the ensuing 9 years.

The economic analysis also includes several uncertain variables. These variables include estimates for the discount rate, time to flood, value of a statistical life and value of unpriced goods. In addition, the probability of a GLOF and its timing was assessed for the decision analysis. Although a diffuse probability distribution was used to reflect the extreme uncertainty in predicting a GLOF, the structuring of the decision tree required assumptions that add to the uncertainty of the analysis, as was discussed in the DA sections above.

METHODOLOGY CONCLUSIONS

The decision making methodology presented here and applied to the two test sites proved to be sufficiently flexible to accommodate both a low and high data case as well as varying geographic locations. Although some of the damage estimation methodologies were originally designed for use in the United States, this work shows that they can be adapted for use in other countries with different building construction characteristics.

In terms of data availability, this methodology can be used for first pass assessments with minimal data. The minimum data needed for the decision making methodology is the flood outline in communities downstream for all flooding scenarios and risk mitigation projects proposed. These can be preliminary estimates of the flood outline. In addition, a first pass estimate of inhabitants and infrastructure in the flood plain is needed. Any information available on the cost of damages and for risk mitigation projects is also useful, although costs for damages can be found via expert elicitation or by adapting cost estimates in another country for the target location as was done for VSL in Nepal and Peru. A minimalist economic assessment can be conducted using the DEA methodology, although the analyst may encounter the problem of too many degrees of freedom if insufficient mitigation projects are assessed or insufficient information is available to bound the value of intangibles. The DA methodology can be used with minimal information by using a diffuse probability distribution (equal probability for all uncertain scenarios), although all consequences must be valued in the same units. Results from a minimalist analysis, however, should not be used for decision making purposes without a sensitivity analysis and careful assessment of the estimates made to ensure they coincide with local values.

The decision making methodology can also be used with more data and more refined estimates of uncertainty. Although the DEA methodology does not allow for the inclusion of uncertainty, the DA methodology can be applied to cases where uncertainty is expressed as a probability distribution. The expected flood damage results can then be used in the DEA. In addition, the high data damage estimate methodologies (HEC-FIA) can be used with site specific information such as mobilization and warning curves, depth-damage curves, and in uncertainty mode when the distribution of uncertain variables is known.

The inclusion of social vulnerability for high data cases provides insight into the characteristics of the population at risk. With site specific demographic information, local knowledge about factors that contribute to social vulnerability, and expert opinion to validate the vulnerability index, decision makers can gain information on how to increase the resilience of the local population to a GLOF event. In addition, using the social risk (vulnerability times hazard index) in the DEA allows for the intangible social damage of a GLOF to be considered in the economic analysis.

The DEA methodology proved to be a useful framework for comparing decisions and assessing them for efficiency, but requires a large field of decisions and bounds on the value of intangibles to provide intangible valuation results. In the Imja Lake analysis, there were insufficient projects to produce unique valuation results for intangible and unpriced damages. The Lake Palcacocha case had sufficient projects to produce cost estimates for intangibles, but in some cases the cost estimates for intangibles were unbounded. Therefore DEA did not consistently provide the results (valuation of intangibles) sought, though the methodology did provided insight into the efficiency of the various projects assessed.

The combination of DA and DEA via a DEA of the expected flood addressed the issue of not being able to incorporate uncertainty into the Data Envelopement Analysis. This approach does not exist in the literature, but is an effective means of combining the two decision making methodologies and provides useful insight to efficient decisions under uncertainty.

FUTURE WORK

This work demonstrates that the decision making methodology coupled with available information on GLOF scenarios, potential damage, and probability produces actionable results that accurately reflect the many unknowns in GLOF risk analysis. The methodology can be applied to a high or low data case and is not site specific. Overall future work should continue testing the limits of the methodology outlined here by applying the methodology at more sites with high and low data. Future research should also be done to verify the scenario and damage estimate methodologies, although this is complicated by the limited data available on how historical GLOFs unfolded and detailed damage reports. Finally, this work should be presented to decision makers at the sites studied to gain feedback on the scenarios and projects studied, damage categories included, cost estimates, and final results of the economic analyses.

As mentioned previously, all updated information pertaining to a GLOF from Imja Lake or Palcacocha Lake should be added to the analyses presented here. New, more accurate information will decrease uncertainty and provide better guidance for decision makers. Site specific future work is described below.

Imja Lake future work

A significant shortcoming for the Imja Lake analysis was the lack of information in terms of the full flood plain for a potential GLOF (further downstream from Dingboche) and cost estimates for damage to infrastructure. At Imja Lake modelling of a GLOF was only conducted through the town of Dingboche. Future work should extend this modelling to communities further downstream and add the damages to the analysis conducted here. Significant damages beyond Dingboche may change the lowest cost decision.

In addition future work should include consultation with experts or community members on the valuation of infrastructure in the region. With better estimates for the monetary value of damages to infrastructure, the DEA will give unique results and the DA will give more accurate estimates of expected costs of each lake lowering project. Another option is to include more projects in the DEA to decrease the degrees of freedom of the problem. However, this analysis uses projects actually under consideration for Imja Lake, and adding projects simply to produce better numerical results is not advisable. Finally, bounds on the value of intangibles or unvalued tangible losses should be estimated (preferably through community consultation) for inclusion in the DEA.

Lake Palcacocha future work

For the Lake Palcacocha site the best decision from an economics standpoint was 30 m lake lowering with EWS; this decision was robust to significant changes in the assumptions used to estimate uncertain variables. Although refinement of the inputs to the analysis would result in a more accurate estimate of the expected cost of each decision, such information is not likely to change the recommended decision. Given that even with the most extreme lake lowering scenario significant damage is still possible to the city center, future work and resources should be dedicated to understanding the vulnerability of populations in the city center and actions that can increase their resilience to a flood. An updated census of the city center with a focus on vulnerability would provide decision makers with a more accurate understanding of the characteristics of this population. In addition, experts should be consulted to verify the vulnerability index. Decision makers can further mitigate damage from a GLOF by understanding the vulnerability of the population at risk and taking measures to educate and build resilience in the region.

References

Abdi, H., 2003. Factor Rotations in Factor Analyses. *Encyclopedia of Social Science Research*, pp.1–8.

Aboelata, M. & Bowles, D.S., 2005. *LIFESim : A Model for Estimating Dam Failure Life Loss*,

Adger, W.N., 2006. Vulnerability. *Global Environmental Change*, 16(3), pp.268–281.

Anderson, M.B., 2000. Vulnerability to Disaster and Sustainable Development: A General Framework for Assessing Vulnerability. In R. P. S. R. Pielke Jr., ed. *Storms*. London, UK: Routlege.

Ang, A.H.-S. & Tang, W.H., 1984. *Probability Concepts in Engineering Planning and Design, Volume II- Decision, Risk, and Reliability*, New York: John Wiley & Sons, Inc.

Awal, R. & Nakagawa, H., 2010. Experimental study on glacial lake outburst floods due to waves overtopping and erosion of moraine dam. *Annuals of Disaster Prevention Research Institute, Kyoto University*, (53).

Bajracharya, S. & Mool, P., 2010. Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal. *Annals of Glaciology*, 50(53), pp.81–86.

Balica, S., 2012. *Applying the Flood Vulnerability Index as a Knowledge base for flood risk assessment*. Ph.D. Diss. UNESCO-IHE, Delft,.

Balica, S.F., Wright, N.G. & Meulen, F., 2012. A flood vulnerability index for coastal cities and its use in assessing climate change impacts. *Natural Hazards*, 64(1), pp.73–105.

Borden, K.A. et al., 2007. Vulnerability of U.S. Cities to Environmental Hazards. *Journal of Homeland Security and Emergency Management*, 4(2).

Byers, A.C. et al., 2013. Glacial lakes of the Hinku and Hongu valleys, Makalu Barun National Park and Buffer Zone, Nepal. *Natural Hazards*, 69(1), pp.115–139.

Byers, A.C. & Thakli, S., 2015. *KHUMBU , NEPAL : LOCAL ADAPTATION PLAN OF ACTION (LAPA)*,

Carey, M. et al., 2011. An integrated socio-environmental framework for glacier hazard management and climate change adaptation: lessons from Lake 513, Cordillera Blanca, Peru. *Climatic Change*, 112(3-4), pp.733–767.

Carey, M., 2010. *In the Shadow of Melting Glaciers: Climate Change and Andean Society*, New York: Oxford University Press.

Carrivick, J.L., 2010. Dam break – Outburst flood propagation and transient hydraulics: A geosciences perspective. *Journal of Hydrology*, 380(3-4), pp.338–355.

Central Reserve Bank of Peru, 2016. *AVERAGE INTEREST RATES - DOMESTIC AND FOREIGN CURRENCY (% ANNUAL EFFECTIVE RATES)*,

CEPAD, 2015. *Detailed Topographical Surveying and Structural Designing of Imja Lake Lowering*, Kathmandu, Nepal.

CEPTE, 2012. Topographic Survey and Engineering Design of the Outlet Channel & Pre-feasibility Study for a Mini-Hydropower Generation Facility from Imja Glacial Lake.

Chambers, R., 2006. Vulnerability, coping and policy (editorial introduction). *IDS Bulletin*, 37(2), pp.33–40.

Cropper, M. & Sahin, S., 2009. *Valuing mortality and morbidity in the context of disaster risks*,

Cutter, S L and Finch, C., 2008. Temporal and spatial changes in social vulnerability to natural hazards. *Pnas*, 105(7), pp.2301–2306.

Cutter, S.L. et al., 2006. The Long Road Home: Race, Class, and Recovery from Hurricane Katrina. *Environment: Science and Policy for Sustainable Development*, 48(2), pp.8–20.

Cutter, S.L., Boruff, B.J. & Shirley, W.L., 2003. Social Vulnerability to Environmental Hazards. *Social Science Quarterly*, 84(2), pp.242–261.

Digital Globe, 2013. Dingboche. , p.27°53’34.6“N 86°49’55.4”E.

Digital Globe, 2015. Dingboche. , p.27°53’36.89“N 86°50’0.06”E.

Emmer, A. & Vilimek, V., 2013. Review article: Lake and breach hazard assessment for moraine-dammed lakes: An example from the Cordillera Blanca. *Natural Hazards and Earth System Sciences*, 13(6), pp.1551–1565.

Eriksen, S.H. & Kelly, P.M., 2006. Developing Credible Vulnerability Indicators for Climate Adaptation Policy Assessment. *Mitigation and Adaptation Strategies for Global Change*, 12(4), pp.495–524.

Eriksson, M. et al., 2009. *The changing Himalayas – Impact of climate change on water resources and livelihoods in the Greater Himalayas*,

Everitt, B. & Hothorn, T., 2011. *An Introduction to Applied Multivariate Analysis with R*, New York Dordrecht Heidelberg London: Springer.

Fields, W. et al., 2012. Dam and Levee Safety Risk Assessment-- Evaluation Routing and Life Loss Estimation Using LIFESIM. In *Innovative Dam and Levee Design and Construction for Sustainable Water Management*. United States Society on Dams, pp. 201–218.

FLO-2D, 2009. *FLO-2D Reference Manual*, Fuchs, S., Birkmann, J. & Glade, T., 2012. Vulnerability assessment in natural hazard and risk analysis: current approaches and future challenges. *Natural Hazards*, 64(3), pp.1969–1975.

Fujita, K. et al., 2009. Recent changes in Imja Glacial Lake and its damming moraine in the Nepal Himalaya revealed by in situ surveys and multi-temporal ASTER imagery. *Environmental Research Letters*, 4(4), p.045205.

Gall, M., 2007. *Indices of Social Vulnerability to Natural Hazards: A Comparative Evaluation*. University of South Carolina.

Garcia-Martinez, R. & Lopez, J.L., 2007. Debris flows of December 1999 in Venezuela. In M. Jakob & O. Hungr, eds. *Debris Flow Hazards and Related Phenomena*. Springer Science & Business Media, pp. 519–539.

Google Earth, 2015. Dingboche. , p.27°53'35.63"N 86°49'57.02"E.

Google Maps, 2016. Dingboche-Chhukhung Path. , p.27°53'48.5"N 86°50'17.6"E.

Graham, W.J., 1999. *A Procedure for Estimating Loss of Life Caused by Dam Failure, DSO-99-06*,

Hambrey, M.J. et al., 2008. Sedimentological, geomorphological and dynamic context of debris-mantled glaciers, Mount Everest (Sagarmatha) region, Nepal. *Quaternary Science Reviews*, 27(25–26), pp.2361–2389.

Hegglin, E. & Huggel, C., 2008. An Integrated Assessment of Vulnerability to Glacial Hazards. *Mountain Research and Development*, 28(3/4), pp.299–309.

Hock, R., 2005. Glacier melt: a review of processes and their modelling. *Progress in Physical Geography*, 29(3), pp.362–391.

Horizons South America S.A.C., 2013. *Informe Tecnico del Proyecto, Consultoria Para el Levantamiento Fotogrametrico Detallado de la Sub Cuenca del Rio Quillcay y la Ciudad de Huaraz Para el Proyecto, Implementacion de Medidas de Adaptacion al Cambio Climatico y Gestion de Riesgos en la Sub*, Lima, Peru.

ICIMOD, 2013. *Case Studies on Flash Flood Risk Management in the Himalayas: In support of specific flash flood policies*, Kathmandu.

ICIMOD, 2011. *Glacial Lakes and Glacial Lake Outburst Floods in Nepal*, Kathmandu.

IDIC, 2016. Instituto de Desarollo e Investigacion Construir. Available at: www.institutoconstruir.org [Accessed April 6, 2016].

INDECI, 2006. *Manual basico para la estimacion del riesgo*, Lima, Peru.

INDECI, 2003. *Plan de prevencion ante desastres: usos del suelo y medidas de mitigacion, Ciudad de Huaraz*,

Investing.com, 2016. Peru 9-year Bond Yield. Available at:

http://www.investing.com/rates-bonds/peru-9-year-bond-yield [Accessed April 29, 2016].

Ives, J.D., Shrestha, R.B. & Mool, P.K., 2010. Formation of Glacial Lakes in the Hindu Kush-Himalayas and GLOF Risk Assessment. *ICIMOD (Inernational Centre for Integrated Mountain Development)*, p.66.

Jaynes, E.T., 1957. Information Theory and Statistical Mechanics. *The Physical Review*, 100(4), pp.620–630.

Johnson, R.A. & Wichern, D.W., 1982. *Applied Multivariate Statistical Analysis*, Englewood Cliffs, NJ: Prentice-Hall.

Karmakar, S., 2010. An Information System for Risk-Vulnerability Assessment to Flood. *Journal of Geographic Information System*, 02(03), pp.129–146.

Karvonen, R. a. et al., 2000. *The Use Of Physical Models In Dam-Break Flood Analysis, Development of Rescue Actions Based on Dam-Break Flood Analysis (RESCDAM)*,

Kattelmann, R., 2003. Glacial Lake Outburst Floods in the Nepal Himalaya : A Manageable Hazard? *Natural Hazards*, 28, pp.145–154.

Keeney, R.L., 1982. Decision Analysis : An Overview. *Operations Research*, 30(5), pp.803–838.

Kortelainen, M. & Kuosmanen, T., 2004. *Data Envelopment Analysis in Environmental Valuation : Environmental Performance , Eco-efficiency and Cost-Benefit Analysis*,

Kuosmanen, T. & Kortelainen, M., 2004. Data Envelopement Analysis in Environmental Valuation: Environmental Performance, Eco-efficiency and Cost-Benefit Analysis. *EconWPA*.

Lehman, W. & Needham, J., *Consequence Estimation for Dam Failures*,

Lempert, R.J., 2003. *Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis*,

Lumbroso, D.M. et al., 2011. Development of a life safety model to estimate the risk posed to people by dam failures and floods. *Dams and Reservoirs*, 21(June), pp.31–43.

MathWorks, 2016. Linear Programming Algorithms. *R2015b Documentation*. Available at: http://www.mathworks.com/help/optim/ug/linear-programming-algorithms.html#buwh0uk-1 [Accessed February 15, 2016].

Di Mauro, M. & Lumbroso, D., 2008. Hydrodynamic and loss of life modelling for the 1953 Canvey Island flood. In *Flood Risk Management-- Research and Practice Proceedings of FLOODrisk 2008*. Oxford, UK, p. 195.

McClelland, D.M. & Bowles, D.S., 2002. *Estimating life loss for dam safety risk assessment--a review and new approach*, Ministerio de Trabajo y Promocion de Empleo, 2007. *Estadisticas Laborales*,

Needham, J.T., Seda-Sanabria, Y. & Bowles, D.S., 2010. *CONSEQUENCE ESTIMATION FOR CRITICAL INFRASTRUCTURE RISK*,

Nepal Rastra Bank, 2016. Current Money and Financial Market Rates. Available at: http://www.nrb.org.np/cmfmrates_details.php?search=02&txtyear1=2015&txtmonth1=01&txtyear2=2015&txtmonth2=12&txtreptype=D [Accessed February 16, 2016].

OMB, 2003. *Circular A-4*,

Petrakov, D.A. et al., 2011. Monitoring of Bashkara Glacier lakes (Central Caucasus, Russia) and modelling of their potential outburst. *Natural Hazards*, 61(3), pp.1293–1316.

Portocarrero, C.A., 2014. *The Glacial Lake Handbook: Reducing Risk From Dangerous Glacial Lakes in the Cordillera Blanca, Peru*,

Rabatel, A. et al., 2013. Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change. *The Cryosphere*, 7(1), pp.81–102.

Rana, B. et al., 2000. Hazard Assessment of the Tsho Rolpa Glacier Lake and Ongoing Remediation Measures. *Journal of Nepal Geological Society*, 22, pp.563–570.

Reynolds Geo-Sciences, 2003. *Development of glacial hazard and risk minimisation protocols in rural environments: Guidelines for the management of glacial hazards and risks*,

Rogers, G.O. & Sorensen, J.H., 1991. Diffusion of Emergency Warning: Comparing Empirical and Simulation Results. In C. Zervos, ed. *Risk Analysis*. New York: Plenum Press, pp. 117–134.

Rounce, D.R. et al., 2016. A New Remote Hazard and Risk Assessment Framework for Glacial Lakes in the Nepal Himalaya. *Hydrology and Earth System Sciences Discussions*, (May), pp.1–48.

Rounce, D.R. & McKinney, D.C., 2014. Debris thickness of glaciers in the Everest area (Nepal Himalaya) derived from satellite imagery using a nonlinear energy balance model. *The Cryosphere*, 8(4), pp.1317–1329.

Rounce, D.R., Quincey, D.J. & McKinney, D.C., 2015. Debris-covered energy balance model for Imja-Lhotse Shar Glacier in the Everest region of Nepal. *The Cryosphere Discussions*, 9(3), pp.3503–3540.

Schmidtlein, M.C. et al., 2008. A sensitivity analysis of the social vulnerability index. *Risk Analysis*, 28(4), pp.1099–1114.

Schneider, D. et al., 2014. Mapping hazards from glacier lake outburst floods based on modelling of process cascades at Lake 513 , Carhuaz , Peru. *Advances in*

Geosciences, 35, pp.145–155.

Sharma, P., Guha-Khasnobis, B. & Raj Khanal, D., 2014. *Nepal human development report 2014*, UNDP and Government of Nepal.

Somos-Valenzuela, M. et al., 2012. Ground Penetrating Radar Survey for Risk Reduction at Imja Lake , Nepal.

Somos-Valenzuela, M.A. et al., 2015. Assessing downstream flood impacts due to a potential GLOF from Imja Tsho in Nepal. *Hydrology and Earth System Sciences*, 19(3), pp.1401–1412.

Somos-Valenzuela, M.A. et al., 2014. Changes in Imja Tsho in the Mt. Everest region of Nepal. *The Cryosphere Discussions*, 8(3), pp.2375–2401.

Somos-Valenzuela, M.A. et al., 2016. Modeling glacial lake outburst flood process chain: the case of Lake Palcacocha and Huaraz, Peru. *Hydrology and Earth System Sciences Discussions*, (January), pp.1–61.

Somos-Valenzuela, M.A., 2014. *Vulnerability and Decision Risk Analysis in Glacier Lake Outburst Floods (GLOF). Case Studies: Quillcay Sub Basin in the Cordillera Blanca in Peru and Dudh Koshi Sub Basin in the Everest Region in Nepal*. The University of Texas at Austin.

The World Bank, 2014. GNI per Capita, PPP. Available at: http://data.worldbank.org/indicator/NY.GNP.PCAP.PP.CD/countries.

UNDP, 2013. *Community Based Flood and Glacial Lake Outburst Risk Reduction Project: Project Document*, Kathmandu, Nepal.

United Nations, 2008. *Living with risk*,

Urothody, A.A. & Larsen, H.O., 2006. Measuring climate change vulnerability: a comparison of two indexes. *Banko Janakari*, 20(1), pp.9–16.

US DOT, 2013. *Revised Departmental Guidance 2013: Treatment of the Value of Preventing Fatalities and Injuries in Preparing Economic Analysis*,

USACE, 2016. HEC-FIA. *US Army Corps of Engineers*. Available at: http://www.hec.usace.army.mil/software/hec-fia/.

USACE, 2015. *HEC-FIA Flood Impact Analysis User 's Manual v 3.0*,

USACE, 2012. *HEC-FIA Flood Impact Analysis User's Manual v 2.2*,

USBUREC, 2014a. *RCEM – Reclamation Consequence Estimating Methodology: Dam Failure and Flood Event Case History Compilation*,

USBUREC, 2014b. *RCEM – Reclamation Consequence Estimating Methodology: Guidelines for Estimating Life Loss for Dam Safety Risk Analysis*,

USDHS, 2011a. *Dams Sector: Estimating Economic Consequences for Dam Failure*

Scenarios,

USDHS, 2011b. *Dams Sector: Estimating Loss of Life for Dam Failure Scenarios*,

Vilímek, V. et al., 2005. Influence of glacial retreat on natural hazards of the Palcacocha Lake area, Peru. *Landslides*, 2(2), pp.107–115.

Watanabe, T., Lamsal, D. & Ives, J.D., 2009. Evaluating the growth characteristics of a glacial lake and its degree of danger of outburst flooding: Imja Glacier, Khumbu Himal, Nepal. *Norsk Geografisk Tidsskrift - Norwegian Journal of Geography*, 63(4), pp.255–267.

Womer, N.K. et al., 2006. Benefit-cost analysis using data envelopment analysis. *Annals of Operations Research*, 145(1), pp.229–250.